

# Energy efficiency improvement and GHG abatement in the global production of primary aluminium

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**Abstract** Primary aluminium production is a highly energy-intensive and greenhouse gas (GHG)-emitting process responsible for about 1 % of global GHG emissions. In 2009, the two most energy-intensive processes in primary aluminium production, alumina refining and aluminium smelting consumed 3.1 EJ, of which 2 EJ was electricity for aluminium smelting, about 8 % of the electricity use in the global industrial sector. The demand for aluminium is expected to increase significantly over the next decades, continuing the upward trend in energy use and GHGs. The wide implementation of energy efficiency measures can cut down GHG emissions and assist in the transition towards a more sustainable primary aluminium industry. In this study, 22 currently available energy efficiency measures are assessed, and cost-supply curves are constructed to determine the technical and the cost-effective energy and GHG savings potentials. The implementation of all measures was estimated to reduce the 2050 primary

energy use by 31 % in alumina refining and by 9 % in primary aluminium production (excluding alumina refining) when compared to a “frozen efficiency” scenario. When compared to a “business-as-usual” (BAU) scenario, the identified energy savings potentials are lower, 12 and 0.9 % for alumina refining and primary aluminium production (excluding alumina refining), respectively. Currently available technologies have the potential to significantly reduce the energy use for alumina refining while in the case of aluminium smelting, if no new technologies become available in the future, the energy and GHG savings potentials will be limited.

**Keywords** Energy efficiency · Primary aluminium industry · Alumina refining industry · Energy savings · GHG savings · Cost-supply curves

## Introduction

The primary aluminium industry comprises one of the top five most energy-intensive industries, following the chemicals and petrochemicals, iron and steel, cement and pulp and paper industries (IEA 2007). In 2009, the final energy consumption for primary aluminium production was about 3.1 EJ,<sup>1</sup> equivalent to 3 % of the total final industrial energy use (excluding industrial non-energy use) (IEA 2011a). Aluminium smelting is a highly electricity-intensive process consuming about

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<sup>1</sup> Estimate based on the 2009 average energy use for alumina refining and aluminium smelting and the 2009 global metallurgical grade alumina production and primary aluminium production (IAI 2013c).

2 EJ of electricity, equivalent to 8 % of the industrial sector's electricity use. The 2009 energy use for alumina refining, the second most energy-intensive process step in the primary aluminium production route, is estimated at 1.1 EJ.

The production of primary aluminium is a multi-stage process. Initially, bauxite ore is resolved/digested and refined into alumina in the Bayer process. Alumina is then transformed into aluminium in an electrolytic cell with the Hall-Héroult process. Molten aluminium is cast into ingots which are transferred and further processed in aluminium foundries. Aluminium can also be produced from scrap, in the secondary production route. Only 5 % of the energy needed to produce primary aluminium is required to produce aluminium from scrap (IEA-ETSAP 2012).

The primary aluminium industry is a large energy consumer and a major greenhouse gas (GHG) emitter as next to the emitted GHG emissions during fuel combustion and electricity generation; perfluorocarbons (PFCs) are emitted. PFCs are gases with a high global warming potential (GWP), ranging from 6,500 times for tetrafluoromethane ( $C_2F_4$ ) and 9,200 times to hexafluoromethane ( $C_2F_6$ ), the GWP<sup>2</sup> of carbon dioxide ( $CO_2$ ) (IPCC 2006b). In 2007, the primary aluminium industry emitted a total of about 400 Mt  $CO_2$  equivalent of GHGs, equivalent to about 1 % of global GHG emissions (IEA 2009b).<sup>3</sup> For the same year, the International Aluminium Institute (IAI) estimates global PFC emissions from aluminium smelting at about 29 Mt  $CO_2$ -eq. (IAI 2013b).

Several studies have addressed the potential for energy efficiency improvements (Saygin et al. 2011) and GHG mitigation (Gale and Freund 2001; Luo and Soria 2007). However, there is currently no study that analyzes the energy and GHG savings potentials of the major energy saving technologies/measures on a country level. Main constraints for a more detailed analysis have been the level of data aggregation. The IAI provides energy use data for alumina and primary

aluminium production on a regional level while the International Energy Agency (IEA) provides energy data on a country level, but they concern the non-ferrous metal industry as a whole.<sup>4</sup>

This study aims to provide a detailed analysis of the current and future energy savings and GHG abatement potentials in the global primary aluminium industry. To achieve this, a bottom-up, computational model of the primary aluminium industry is developed, to construct cost-supply curves depicting the energy and GHG savings potentials and the costs per country. Two scenarios are developed, the “frozen efficiency” and the “business-as-usual” scenarios. The frozen efficiency scenario estimates the energy and GHG development when energy intensity remains at current levels, and the business-as-usual when progress takes place based on historical rates.

In addition, this study attempts to investigate the potentials for energy savings in alumina refining. Main reason is that, and as already identified in several studies (Saygin et al. 2011; Green 2007), although alumina refining is a less energy-intensive process than aluminium smelting, it offers potentially large savings in the production chain of aluminium. According to Saygin et al. (2011), the worldwide adoption of best practice technology (BPT) in the primary aluminium industry can decrease the energy use by 24 %, with improvements in alumina refining being responsible for 80 % of the total savings potential. The relatively low-energy savings potential identified for aluminium smelting reflects the fact that the smelting of aluminium, following its identification as a major energy-intensive process, has already been significantly optimized (Green 2007). In addition, innovative technologies, able to further decrease energy use, are still in pilot phase.

In this paper, we give an overview of the primary aluminium industry, briefly describing the main processes, along with the energy intensities and the main sources of GHG emissions (“Overview of the primary aluminium industry”). We then describe the methodology followed to construct the cost-supply curves in “Methodology” section and give an overview of the most important energy efficiency improvement technologies/measures in “Review of energy efficiency

<sup>2</sup> The GWPs used in this analysis are the 100-year values reported in the second IPCC Assessment Report (IPCC 1995).

<sup>3</sup> It includes  $CO_2$  emissions from fuel combustion, indirect  $CO_2$  emissions from electricity consumption and process emissions from aluminium smelting. The most important process emissions in primary aluminium production are i)  $CO_2$  emissions released during the consumption of carbon anodes, and ii) PFC emissions released when the alumina concentration in the electrolytic cell drops below a critical point.

<sup>4</sup> In 2009 the non-ferrous metals industry consumed about 4.3 EJ (IEA, 2011a). It is estimated that the two most energy intensive steps in primary aluminium production (alumina refining and aluminium smelting) were responsible for about 72 % of the energy consumed in the non-ferrous metals industry.

improvements” section. In “Results and discussion” section, we present the results and the discussion and in “Conclusion and recommendations” section the conclusion along with our recommendations.

## Overview of the primary aluminium industry

Although aluminium is a relatively new material, produced for the first time in early 1800, its wide versatility has triggered demand, and primary aluminium production surpassed the 49 Mtonnes in 2013. That is about two times the 2001 production and more than four times the 1973 production, or an average annual growth within the 1973–2013 period of 3.6 %, but grew more rapidly in later years. The aluminium industry faces a growing demand with the main driver being China.

The structure of the primary aluminium industry is not the same as 40 years ago. Alumina production has shifted from industrialized or primary aluminium-producing countries (i.e. USA, Japan, Canada, France and Germany), to countries rich in bauxite reserves (IAI 2013d). A similar shift has been observed in the aluminium smelting industry. Three countries, USA, Union of Soviet Socialist Republics (USSR) and Japan responsible for 60 % of primary aluminium production in the early 1970s, currently supply only 10 % of primary aluminium. In the past years, aluminium production has grown in Australia, Canada, Russia, China and Middle East with main reason for most countries being the low electricity costs (IAI 2013d).

Electricity and alumina costs account for about 22 and 31 % of production costs, respectively (Bergsdal et al. 2004); therefore, access to abundant and low-cost electricity and alumina is of major importance. New aluminium smelting plants are usually built in areas where production costs are low. According to IAI (2013d), in 2009, 38 % of electricity used in aluminium smelting came from hydropower. Countries with abundant hydropower are Brazil, Canada, Norway and Russia.

Energy efficiency in aluminium smelting has notably improved over the past decades. In the 1950s, electricity use amounted to 21 MWh/tonne aluminium (Bergsdal et al. 2004) and decreased to 17 MWh/tonne in the 1980s. Current world average energy use has reached 14.8 MWh/tonne aluminium (IAI 2013c). Some developing countries currently have some of the lowest

energy intensities, since new plant capacities installed were based on more recent and efficient technologies.

## Production processes and energy use

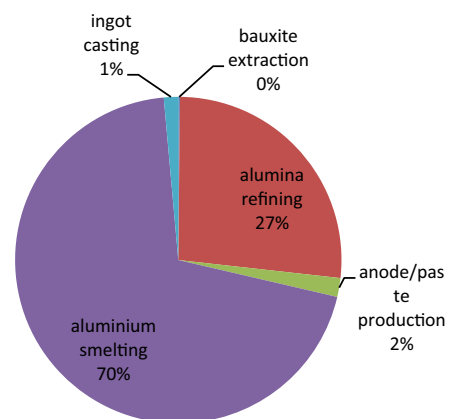
As shown in Fig. 1, the most energy-intensive processes in primary aluminium production are alumina refining and aluminium smelting, responsible for 27 and 70 % of energy use, respectively. Anode production is responsible for about 2 %, while aluminium casting for about 1.4 % of the energy use (IAI 2013a).

### Bauxite extraction

Bauxite ore is usually mined in open pit mines, in certain cases, washed and dried, and when originating from forested areas also beneficiated. Energy use is mainly fuel used by excavating equipment and varies based on the depth of bauxite sources. The 2010 IAI Life Cycle Inventory (LCI) reports an energy use of 23 MJ/tonne bauxite (IAI 2013a), while the 2005 data on the North American aluminium industry give an energy use of 216 MJ/tonne bauxite (Green 2007). Approximately 2.9 tonnes of bauxite are required to produce 1 tonne of alumina (IAI 2013a).

### Alumina refining

Bauxite is transferred to alumina refineries for the production of alumina. The process most widely used is the Bayer process in which bauxite is forwarded to a series of digesters where it is dissolved in most cases in a mix of sodium hydroxide and sodium carbonate under



**Fig. 1** Energy use breakdown in primary aluminium production (based on data reported in IAI 2013a)

**Table 1** Energy intensities for different alumina refining processes

	Bayer	Sinter	Combined Bayer-Sinter	Flotation-Bayer	Lime-Bayer	Nepheline
GJ/tonne alumina	8–13.6 <sup>1</sup>	36–40.5 <sup>2</sup>	21–52 <sup>3</sup>	16.0–16.1 <sup>4</sup>	16.3 <sup>5</sup>	50 <sup>6</sup>

<sup>1</sup> IPTS/EC 2013; Smith 2009; Liu et al. 2010; <sup>2</sup> Smith 2009; Liu et al. 2006; Liu et al. 2010; <sup>3</sup> Liao and Li 2010; Li et al. 2008; Liu et al. 2006; <sup>4</sup> Li and Yang 2010; Liu et al. 2010; <sup>5</sup> Liu et al. 2010; <sup>6</sup> Smimov 1996

pressure and temperature (BCS 2007). The product of digestion, “green liquor”, is then clarified to remove the undesirable bauxite residue, commonly known as “red mud”, and the alumina hydrate dissolved in the liquor is subsequently precipitated (“crystallized”) and calcined (removal of crystal water) in rotary or stationary calciners. Typical energy use is 4–10 GJ/tonne for digestion and evaporation and 3–4.5 GJ/tonne for calcination. In addition, electricity needs raise the overall energy use by another 1.0 GJ/tonne (Henrickson 2010). The total energy consumption in alumina refining is mainly influenced by the quality of bauxite ore, the selected digestion technology, the type of calciner (IPTS/EC 2013) and the plant liquor productivity (“yield”) (Donaldson 2011).

Bauxite quality plays an important role in energy use. The use of bauxite with high-water content will increase the energy use due to higher evaporation needs (IPTS/EC 2013). In addition, monohydrate bauxite ores (boehmite and diaspor) require higher pressure and temperature in digestion than tri-hydrates (gibbsite) (IPTS/EC 2013; BCS 2007). Also, a high reactive silica content results in increased operating costs as it reacts to form sodium aluminium silicates which precipitate, binding aluminium and sodium values. Bauxites with high silica content (8–15 %) are processed in alternative and more energy-intensive processes than the Bayer to improve alumina and sometimes sodium recovery. Such processes are the combined Bayer-Sinter, the Sinter, the Flotation-Bayer and the Lime-Bayer processes. Table 1 presents typical energy intensities.

The combined Bayer-Sinter and the Sinter processes have been widely used in China and Russia due to the low-quality bauxite reserves available in these regions. It is reported that China decreased the combined Bayer-Sinter share from 88 % in 2005 (Yanjia and Chandler 2009) to 15 % in 2009 (Gu and Wu 2012) significantly decreasing

its energy use. In a few areas in Russia and Iran, alumina is produced from nepheline concentrate.<sup>5</sup> The nepheline process produces a variety of materials (i.e. cement, soda, potash and alumina). Figure 2 shows the share of the different processes in alumina production in China and Russia in 2009.

In the digestion area, tube digestion in which the bauxite slurry is heated without being diluted with live steam is considered an energy efficient technology for bauxites requiring high-temperature digestion (temperature >240 °C). In the calcination area, stationary kilns, due to improved waste heat recovery, consume 30 % less energy than rotary calciners (Missalla et al. 2011; Klett et al. 2011).

A key factor affecting energy consumption in alumina refineries is the plant liquor yield—the alumina produced per cubic meter of liquor pumped around the Bayer plant (Henrickson 2010; Hudson et al. 2005; Donaldson 2011). The alumina throughput is equal to the flow times the yield. Hence, increasing the refinery’s yield will translate into a lower flow needed to satisfy production and therefore decreasing the energy requirements (Henrickson 2010).

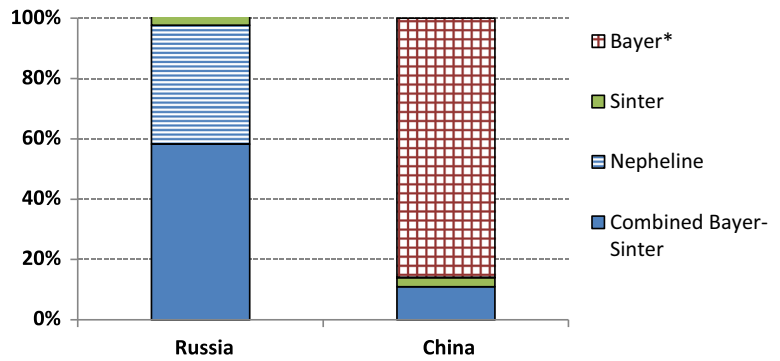
Optimizing the alumina refining process can reduce the energy use to below 7 GJ/tonne alumina in alumina refineries using tube digestion and below 10 GJ/tonne alumina for a conventional digestion system (IPTS/EC 2013).

In 2009, the worldwide average energy use in alumina refining was 14.6 GJ per tonne of alumina (IAI 2013c). More than 90 % of the energy used is fuel with the remainder being electricity (IAI 2013a). The energy use in alumina refining has experienced an annual decrease of 0.4 % during the 1998 to 2012 period.<sup>6</sup> Table 2

<sup>5</sup> Nepheline concentrate is a by-product deriving from beneficiation factories, which contains about 25–30 % alumina and 44 % silica (Smimov 1996).

<sup>6</sup> This was estimated based on the reported energy use for alumina refining (IAI 2013c) for the 1998–2012 period. Although energy use data are also available for earlier years, China started reporting energy use data in 1998.

**Fig. 2** Production shares of the various alumina refining processes in 2009, in China and Russia [based on UC Rusal (2010) for Russia and Gu and Wu (2012) for China] \*includes alumina produced with the Bayer, Flotation-Bayer and the Lime-Bayer processes. In 2005, about 13 % of Chinese alumina production derived from the Bayer process (Yanjia and Chandler, 2009)



shows the energy use in the six top alumina-producing countries in 2009.

### Carbon anode production

Carbon anodes are consumed during electrolysis. There are two types of carbon anodes used in electrolytic cells, i.e. Söderberg (in situ baked) and prebaked anodes. Prebaked anodes are more energy efficient and are characterized by lower PFC and process CO<sub>2</sub> emissions (see Table 4). There are two types of Söderberg anodes, vertical stud Söderberg (VSS) and horizontally stud Söderberg (HSS), and three types of prebaked anodes, varying in the way the busbars transfer electric current to the electrolytic cell, side-worked prebake cells (SWPB), center-worked prebake cells (CWPB), and the most energy efficient, prebake cells with point-feeding system (PFPB). All new primary aluminium-producing facilities install PFPB cells (BCS 2007). Currently, about 90 % of aluminium is produced in prebaked cells (IAI 2013a).

Anode production facilities can be situated at the smelting site or in specialized anode baking facilities. Prebaked anodes are made from calcined petroleum coke, coal tar or petroleum pitch and cleaned recycled anodes (butts) (BCS 2007; IPTS/EC 2013) which are baked in open or closed ring furnaces at 1,100 °C (IPTS/EC 2013). According to the 2010 LCI, the energy requirements are 526 and 3,750 MJ/tonne for Söderberg and prebake anodes, respectively. Electrolysis in prebake cells requires 0.43 tonnes of anode while Söderberg electrolysis 0.53 tonnes of anode per tonne aluminium produced (IAI 2013a). BPT energy use for prebake anode baking is 2.8 GJ/tonne anode (Worrell et al. 2008).

### Aluminium smelting

Primary aluminium is produced with the electrochemical reduction of alumina by the Hall-Héroult process. The Hall-Héroult process takes place in an electrolytic cell consisting of two electrodes, an anode and a cathode, separated by an electrolytic bath (usually cryolite). A direct current (DC) enters through the anode into the electrolytic bath where alumina is dissolved and exits through the cathode. The DC current reduces alumina into aluminium and oxygen. Aluminium is extracted through siphons at the upper part of the cathode, and oxygen reacts with the carbon anode to form carbon dioxide (BCS 2007).

The Hall-Héroult process is the most energy-intensive step in the primary aluminium production chain, responsible for nearly 70 % of the overall final energy consumed and 98 % of the electricity consumed (IAI 2013a). Electricity use differs per type of electric cell with the typical values shown in Table 4. According to the 2010 LCI, Söderberg cells consume 17.2 MWh/tonne aluminium and prebake cells 15 MWh/tonne aluminium (IAI 2013a). Electricity use in state-of-art smelters is about 13.5 MWh per tonne (IEA 2009b).

In 2009, the world average electricity use<sup>7</sup> was 14.8 MWh/tonne of primary aluminium (IAI 2013c). During the past two decades, the energy use in aluminium smelting has experienced an annual decrease of 0.4 % (IAI 2013c). Electricity use differs between the different countries due to

<sup>7</sup> In this study, and unless otherwise mentioned, electricity use refers to alternating current (AC) electricity. AC electricity is the DC electricity plus the electricity use in auxiliary components. Electricity use in alumina refining, anode manufacture and ingot casting is not included.

**Table 2** Alumina production and energy intensity in the main alumina-producing countries in 2009

Countries	Alumina production (10 <sup>3</sup> tonnes) <sup>1</sup>	Estimated alumina production-metallurgical grade (10 <sup>3</sup> tonnes) <sup>2</sup>	Share on global production (%)	Energy intensity <sup>3</sup> (GJ/tonne alumina)	Sources for energy use
China	23,800	22,938	31 %	19.4	IAI, 2013c
Australia	19,948	19,649	26 %	10.5	AAC, 2012
Brazil	8,618	8,544	11 %	9.6 <sup>4</sup>	IAI, 2013c
India	3,900	3,347	5 %	14.4	Trudeau et al., 2011
Russia	2,794	2,568	4 %	27.9 <sup>5</sup>	own calculations based on UC Rusal, 2010; Liu et al., 2010
United States	2,370	1,961	3 %	14.4	Green, 2007
Rest	15,270	13,268	20 %	N/A	–
<i>Total</i>	<i>76,700</i>	<i>72,723</i>	<i>100 %</i>	<i>14.6</i>	<i>IAI, 2013c</i>

<sup>1</sup> Alumina production data are taken from USGS (2012b)

<sup>2</sup> Reported alumina production on a country level includes alumina produced for metallurgical and chemical purposes. Most of alumina produced (about 94 % in 2009) (IAI 2013c) is of metallurgical grade. To exclude the chemical grade alumina production, we use the regional shares of metallurgical alumina to the overall alumina production reported by IAI (2013c) (see Table 14 in the Appendix)

<sup>3</sup> Energy intensity in alumina refineries in 2009. When no data are available for 2009, the most recent available data found in literature are used

<sup>4</sup> Due to the lack of data, the energy use of the Brazilian alumina industry is assumed to be equal to the 2009 energy use in Latin America as reported by the IAI (2013c). The fuel oil consumption for alumina refining reported in Brazilian statistics (Ministerio de Minas E Energia 2012), translates into a very low energy intensity of about 5 GJ/tonne alumina, which most probably only accounts for the calcination process

<sup>5</sup> Estimated based on the 2009 share of the different alumina refining production processes in Russia (see Fig. 2) and an energy intensity of 26 GJ/tonne for the Combined Bayer-Sinter process (Liu et al. 2010) and 38 GJ/tonne alumina for the Sinter process (Smith 2009). This value does not take into account alumina production with the Nepheline process

the different cell technologies employed and the level of energy efficiency. Table 3 shows the primary aluminium production in the top primary aluminium-producing countries.

### Ingot casting

After electrolysis, the liquid metal is kept in holding induction or reverberatory furnaces for alloying (IPITS/EC 2013). Molten aluminium is then turned into solid shapes, through ingot casting, which will be further processed in extrusion, casting and rolling facilities. Remelt ingot and recycled aluminium scrap are also used. In general, ingot casting is not very energy intensive. Based on the 2010 LCI, about 1,120 MJ/tonne aluminium is used in ingot casting, of which 88 % is fuel and 22 % electricity (IAI 2013a), while 2005 data on the North American aluminium industry give an energy use of 3,600 MJ/tonne aluminium (Green 2007).

### Greenhouse gas emissions

Primary aluminium production is a significant source of carbon dioxide (CO<sub>2</sub>) and perfluorinated hydrocarbon (PFC) emissions. CO<sub>2</sub> emissions are generated during (i) anode consumption (process CO<sub>2</sub> emissions)<sup>8</sup> and (ii) fuel combustion and electricity generation (when based on fossil fuel use). In addition, PFCs, CF<sub>4</sub> and C<sub>2</sub>F<sub>6</sub>, gases with 6,500 and 9,200 times the GWP of CO<sub>2</sub>, respectively (IPCC 2006b), are emitted when the alumina content in the electrolytic cell drops below a critical level, a critical condition known as the “anode effect”. Based on the IAI (2013c), in 2009, about 22.1 MtCO<sub>2</sub>-eq. was emitted. According to the same source, the global mean PFC emission inten-

<sup>8</sup> The majority of process related CO<sub>2</sub> emissions derive from the reaction of alumina with the anode ( $2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$ ). The CO<sub>2</sub> emissions associated with the baking of prebake anodes account for less than 10 % of the overall process related CO<sub>2</sub> emissions. (IPCC, 2006b)

**Table 3** Primary aluminium production and energy intensity in the main primary aluminium producing countries in 2009

Countries	Primary aluminium production (10 <sup>3</sup> tonnes) <sup>1</sup>	Share in global production (%)	Electricity intensity (MWh/tonne aluminium)	Sources for energy use
China	12,900	35 %	14.2	IAI, 2013c; IEA, 2012; Li and Yang 2010
Russia	3,815	10 %	14.9	IEA, 2012
Canada	3,030	8 %	14.7 <sup>2</sup>	own calculations based on CIEEDAC, 2012
Australia	1,943	5 %	15.0	AAC, 2012
United States	1,727	5 %	15.4	IEA, 2012
India	1,598	4 %	14.9	IEA, 2012
Brazil	1,536	4 %	15.6	IEA, 2012
Norway	1,130	3 %	13.5 <sup>3</sup>	Grimsrud and Kvinge, 2006
United Arab Emirates	1,010	3 %	14.8 <sup>4</sup>	IAI, 2013c
Bahrain	848	2 %	14.8 <sup>4</sup>	IAI, 2013c
South Africa	809	2 %	14.9	IEA, 2012
Rest	6,754	18 %		
<i>Total</i>	<i>37,100</i>	<i>100 %</i>	<i>14.8</i>	<i>IAI, 2013c</i>

<sup>1</sup> Primary aluminium production data were taken from USGS (2012a)

<sup>2</sup> The electricity use reported in CIEEDAC (2012), 14.8 MWh/tonne aluminium, also includes the electricity use in alumina refining, anode production and ingot casting. To estimate the electricity use only for aluminium smelting, we initially estimate the electricity use in the remaining processes based on the alumina and primary aluminium 2009 production levels, the share of the prebake and Söderberg anodes in Canada (see Table 24 in the Appendix), and the average material and electricity requirements for each process step (based on IAI, 2013a) and subtract it from the reported value

<sup>3</sup> 2005 electricity use

<sup>4</sup> Due to the lack of data, the energy use for aluminium smelting in Bahrain and the United Arab Emirates is assumed to be equal to the energy use reported by the IAI for the Gulf Cooperation Council (GCC) region (Bahrain, Oman, Qatar and United Arab Emirates). Bahrain and the United Arab Emirates are responsible for 84 % of primary aluminium production in the GCC region

sity decreased from about 4.5 in 1990 to 0.59 tCO<sub>2</sub>-eq./tonne aluminium by 2009.

Table 4 shows the typical process CO<sub>2</sub> and mean PFC emission intensities per different type of cell technology in 2009. PFC emissions depend on the duration and frequency of anode effects and the overvoltage during the effect. Improved process control and alumina point-feeding systems can limit the occurrence and duration of anode effects (IPTS/EC 2013).

The indirect CO<sub>2</sub> emissions from electricity consumption in smelting differ widely per country as they depend on the fuel mix used for electricity generation.

## Methodology

A bottom-up model has been constructed to generate energy and GHG cost-supply curves for the major alumina and primary aluminium-producing

countries. The model uses disaggregated data on the specific energy use<sup>9</sup> of the different processes in the various countries.

Cost-supply curves are a useful tool, used to present the cost-effective as well as the technical energy and GHG savings potentials. To construct the curves, the most important energy and GHG emission mitigating measures/technologies, commercially available today, are identified and ranked from low to high based on their cost of conserved energy (CCE), or cost of mitigated greenhouse gases (C<sub>CO<sub>2</sub>-eq.</sub>). The cost-supply curves show, in the y-axis, the CCE or the C<sub>CO<sub>2</sub>-eq.</sub> and, in the x-axis, the cumulative energy savings and the cumulative GHG emission savings. The width of each segment in the

<sup>9</sup> Specific energy use is the sum of the energy-related fuels and electricity used in the manufacture of the various products in primary aluminium production. Energy use for transportation and life cycle energy use is not taken into account.

**Table 4** Energy intensity and PFC and process CO<sub>2</sub> emission intensity per cell technology type (Schwarz et al. 2001; IAI 2013c and IAI 2013a)

Cell technology	Energy intensity (MWh/tonne aluminium) <sup>1</sup>	2009 mean PFC emission intensity (tCO <sub>2</sub> -eq./t aluminium)	Process CO <sub>2</sub> emissions (tCO <sub>2</sub> /t aluminium)	Technology distribution
CWPB	14.6	0.7		3 %
PFPB (non-China)	14.4	0.3	1.5	43 %
PFPB (China)		0.7		44 %
SWPB	15.5	4.3		1 %
VSS	16.1	1.0	1.6	8 %
HSS	16.6	1.3		1 %
<i>Overall</i>	<i>14.8</i>	<i>0.6</i>	<i>N/A</i>	<i>100 %</i>

<sup>1</sup>The energy intensities per different cell type are based on 1995 data (Schwarz et al., 2001)

graph shows the energy or GHG savings potential of each energy efficiency improvement measure.

The CCE and the C<sub>CO<sub>2</sub>-eq</sub> can be determined with the use of Eqs. 1 and 2, respectively.

$$CCE = \frac{\text{Annualized investment cost} + \text{Annual O\&M cost} - \text{Annual Financial benefits from energy savings}}{\text{Annual energy savings}}$$

$$C_{CO_2\text{-eq}} = \frac{\text{Annualized investment cost} + \text{Annual O\&M cost} - \text{Annual Financial benefits from energy savings}}{\text{Annual GHG emission savings}}$$

The annualized investment cost is a function of the discount rate and the technical lifetime of the technology and can be calculated from Eq. 3.

$$\text{Annualized investment cost} = \text{Investment cost} \times \frac{d}{(1 - (1 + d)^{-n})}$$

Where  $d$  is the discount rate (%) and  $n$  the technical lifetime in years of the measure.

The cost-effective energy savings potential is defined as the sum of the energy savings potentials of all measures with a CCE less than 0. Technical energy savings potential is defined as the sum of all energy savings potentials of all the measures identified in this study. For the estimation of the technical potentials, no financial constraints are taken into consideration.

To determine the annualized investment costs, the discount rate needs to be defined. Social discount rates typically range between 6 and 8 %, while private discount rates are relatively higher and often range between 30 and 50 % (Laitner et al. 2003). The use of higher discount rates aims at reflecting the hurdle rates of

private investors to adopt energy efficiency measures (Worrell et al. 2004). The discount rates used in different studies vary considerably, with high discount rates being considered more representative of the industrial sector (Martin et al. 2000; Fleiter et al. 2009). In this study, to show the stakeholders' difficulty to invest in projects with high initial investment costs and long payback periods, a discount rate of 30 % is used. To assess the cost-effectiveness of the different measures under different discount rates, a sensitivity analysis is performed in "Results and discussion" section.

Energy consumption and GHG emissions in the primary aluminium industry can be reduced through the replacement or retrofitting of existing processes with technologies/measures with increased energy efficiency. The measures identified in this study are obtained from technical information found in literature and information offered from industry experts (see "Review of energy efficiency improvements" section).

The methodology followed for the construction of the bottom-up model that generates cost-supply curves able to determine the cost- and non-cost-effective



energy and GHG savings potentials for the primary aluminium is the following:

1. *Establish the base year.* For this study, 2009 was chosen as the base year, as it was the most recent year for which information on energy use for alumina refining and aluminium smelting was available on a country level.
2. *Determine the geographical boundaries.* It is very data intensive to include all the primary aluminium and alumina-producing countries in the bottom-up model. For this reason, the top 11 primary aluminium (China, Russia, Canada, Australia, USA, Brazil, Norway, United Arab Emirates, Bahrain and South Africa) and top 6 alumina (China, Australia, Brazil, India, Russia and the USA) producing countries are taken into account responsible for the 82 and 80 % of overall production, respectively (for more details on country production levels, see Tables 2 and 3).
3. *Determine the project boundaries.* The processes considered in this study are (i) alumina refining, (ii) anode production, (iii) aluminium smelting and (iv) ingot casting. The energy use and GHG emissions of input material (i.e. caustic soda, limestone calcination and cathode carbon production) needed in the production of primary aluminium are excluded from this analysis.
4. *Determine the base year energy use and GHG emissions.* The 2009 energy consumption for alumina refining and aluminium smelting per country is estimated by multiplying the specific energy use and production in Tables 2 and 3. Information regarding the energy use for anode production and ingot casting is not available on a country level. Therefore, in the case of anode manufacturing, we multiply the average energy use of Söderberg and prebake anode making with the primary aluminium production per different cell technology in each country. The estimated share of Söderberg and prebake technology per country is shown in Table 24 in the Appendix. In the case of ingot casting, we multiply the average energy use for ingot casting with the primary aluminium production.

To estimate the GHG emissions from fuel consumption, the overall fuel use is broken down per fuel type and then multiplied by the typical emission factor of the specific fuel (see Table 15 in the Appendix). The fuel mix used for each country is

based on the reported fuel mix for the non-ferrous metal industry in IEA statistics (2011a) (see Table 16 in the Appendix).

GHG emissions from electricity use will depend on the fuel mix used for electricity generation and the associated conversion efficiency. Aluminium smelting relies heavily on hydropower with 38 % of electricity in 2009 deriving from hydro sources (IAI 2013d). As alumina refineries are primarily situated close to bauxite reserves<sup>10</sup> and not close to aluminium smelters, the electricity consumed is generated from a different fuel mix than in smelters. In this study, the fuel mix used for generating electricity consumed in alumina refineries is similar to the electricity coming from the grid in each country based on IEA statistics (2011a). For aluminium smelters, we first define the share of hydropower on a country basis based on information available in literature, and then, we break down the remaining share of electricity based on the fuel mix used in the grid. The fuel mix for electricity generation for alumina refining and aluminium smelting and the conversion efficiencies are given in Table 17, Table 18, and Table 19 in the Appendix.

5. *Determine the baseline scenarios.* To estimate the future cost- and non-cost-effective potentials, a baseline scenario that shows the future development of the energy demand in primary aluminium production needs to be determined. Future energy demand will be a function of primary aluminium demand.

#### 5a. Future material demand

To estimate the future primary aluminium production, we assume that in the 2009–2050 period, primary aluminium production will increase with gross domestic product (GDP). According to CRU (2006), world average primary aluminium production is expected to reach 65 Mtonnes in 2025, an annual growth of 2.7 % in the 2010–2025 period, analogous to about three quarters of global GDP growth.

Not all countries are expected to experience the same growth. In China, primary aluminium production experienced a fivefold increase in the 1999–2009 period, while more recently, production increased by 40 % from about 9 Mtonnes in 2006 to

<sup>10</sup> It should be noted that this does not apply to US and European alumina refineries, some of the Australian refineries and two large Brazilian refineries.

13 Mtonnes in 2009 (IAI 2013a). As in other countries, this growth is expected to decrease as the economy will start shifting from infrastructure to services. The reduction in China, however, is expected to be more significant than in other countries. The main reason is that the strong increase in the early 2000s was due to favourable governmental conditions—around 80 % of the outdated and energy-intensive Söderberg aluminium smelters instead of shutting down, were renovated and increased their capacity—and not due to low production costs (CRU 2006). Another reason Chinese smelting capacity increased was due to the exploitation of electricity from isolated coal power plants that were difficult to

connect to the grid (CRU 2006). This cannot be sustainable in a country such as China, characterized by high electricity prices (see Table 5). Thus, primary aluminium production growth in China, after 2010, is expected to deteriorate drastically (CRU 2006).

On the other hand, India's aluminium demand is expected to further increase in the future, since aluminium will be needed in the infrastructure, residential, and automotive sectors and in a growing aerospace industry.

In this study, we assume that the primary aluminium production growth rate in the top 11 primary aluminium-producing countries will equal three fourths of GDP growth (based on CRU 2006).

**Table 5** Fuel and electricity prices in 2008, 2009 (EIA, 2013b; IEA, 2008)

	China	Russia	Canada	United States	Australia	Brazil	Norway	India	United Arab Emirates	Bahrain	South Africa
Natural gas (\$/GJ)	10.5 <sup>1</sup>	2.0	4.1	4.8	5.4 <sup>2</sup>	11.8 <sup>3</sup>	6.2 <sup>4</sup>	4.0 <sup>5</sup>	1.0 <sup>7</sup>	1.0 <sup>6</sup>	7.7 <sup>8</sup>
Steam coal (\$/GJ)	2.0 <sup>9</sup>	1.7	2.4	3.1	3.0 <sup>10</sup>	1.8 <sup>3</sup>	4.5 <sup>4</sup>	1.8	–	–	0.9 <sup>8</sup>
Heavy fuel oil (\$/GJ)	12.1 <sup>11</sup>	8.5 <sup>12</sup>	13.0	12.9	16.9 <sup>2,13</sup>	6.8 <sup>3</sup>	13.1 <sup>4</sup>	12.7 <sup>14</sup>	– <sup>15</sup>	–	10.7 <sup>14</sup>
Electricity											
(alumina refining) (\$/MWh)	105 <sup>16</sup>	50	59 <sup>17</sup>	68	51 <sup>2</sup>	120	64	69 <sup>18</sup>	–	–	22 <sup>9</sup>
Electricity (aluminium smelting, anode production and ingot casting) (\$/MWh) <sup>19</sup>	56	25	17	34	21	28	25	31	24	24	17

– Not applicable

<sup>1</sup> Natural gas prices for the industrial sector vary considerably between the different Chinese provinces. In 2008, natural gas prices ranged between \$5 and \$15/GJ (IEA 2009c). In this study we use an average price of \$10.5/GJ

<sup>2</sup> These are the energy prices in the Australian primary metal and metal product manufacturing industry (ABS 2010)

<sup>3</sup> 2006 data (IEA 2009a)

<sup>4</sup> Energy costs in manufacturing mining and quarrying (Statistics Norway, 2010)

<sup>5</sup> IEA 2010

<sup>6</sup> 2006 data (ALBA 2010)

<sup>7</sup> Due to the lack of data it is assumed equal to the natural gas price in Bahrain

<sup>8</sup> 2005 data

<sup>9</sup> 2004 data

<sup>10</sup> (BREE, 2013)

<sup>11</sup> Due to lack of data we use the 2008 heavy fuel oil price reported for Chinese Taipei

<sup>12</sup> (IEA 2009a)

<sup>13</sup> As oil consumption in the Australian industry is mainly diesel oil (EIA 2013a), this energy price is for diesel oil

<sup>14</sup> 2007 data (IEA 2009a)

<sup>15</sup> No data are available, however the share of oil use in the fuel mix is low (see Table 16 in the Appendix)

<sup>16</sup> IEA (2011b)

<sup>17</sup> 2006 data

<sup>18</sup> Abeberese (2013)

<sup>19</sup> 2009 electricity prices for smelters. Based on country and regional prices (CRU, 2010)

Exceptions are China for which production growth will equal half of the increase in GDP growth and India for which production growth will equal the GDP growth. Secondary aluminium production is outside the project boundaries; thus, the 2050 secondary aluminium production is not estimated. The GDP growth rates used are based on IEA (2011c) (see Table 20 in the Appendix).

As about 1.93 tonnes of alumina are required to produce 1 tonne of aluminium, the global alumina production in 2050 will equal 1.93 times the 2050 estimated global primary aluminium production. Important though for this study is to estimate the alumina production in the top six alumina-producing countries. Future alumina production in the different countries will primarily depend on production costs and the access to good quality and low-cost bauxite. In this study, an oversimplified method is used to determine future alumina production on a country basis. It is assumed that for the alumina-exporting countries (Australia and Brazil) but also for India, the alumina production share on global production remains the same as in 2009. For China, we assume that 14 % of the alumina required in Chinese primary aluminium production is imported (same as in 2009) (based on Storesund 2012). Similarly, we assume that 44 and 60 % of alumina demand of US (based on USGS 2011) and Russian smelters (author own estimation<sup>11</sup>), respectively, is imported (same as in 2009).

Figure 3 shows the breakdown of alumina and primary aluminium production per different country in 2009, 2035 and 2050. We estimate that in 2050, global primary aluminium production will increase to 95 Mtonnes while global alumina production will increase to 183 Mtonnes, an annual increase of about 2.3 %.

The future primary aluminium production estimated in this study matches well with the production estimated by IEA (2012) under the low-demand scenario according to which primary aluminium production will rise to 90–100 Mtonnes by

2050. In the same study and under the high-demand scenario, primary aluminium production is forecasted to increase to 120–135 Mtonnes.

Future primary aluminium and alumina projections have a great impact on the estimated future energy use and GHG emissions and the estimated energy and GHG savings potentials. The primary aluminium production in this analysis was based on future GDP trends. We used this approach to estimate the future primary aluminium production as many studies (Cleveland and Ruth 1998; de Bruyn and Opschoor 1997) have shown that an economy's material intensity increases with GDP and starts a decreasing trend as a certain income level is reached. As development takes place, economies industrialize and build up infrastructure, increasing the intensity of material use which starts decreasing when societies become more affluent, with their economies relying mostly on services. In this stage, when structural change occurs, de-materialization starts (Neelis and Patel 2006). The degree of dematerialization can be debated though, as according to a recent study (Wiedmann et al. 2013), it can be lower than it was initially expected.

In reality, which countries will increase their share on world primary aluminium and alumina production will depend on their comparative advantage. Thus, this analysis could benefit from a more detailed way of projecting future production that takes into account parameters such as energy and raw material prices and trade.

#### 5b. Baseline scenarios

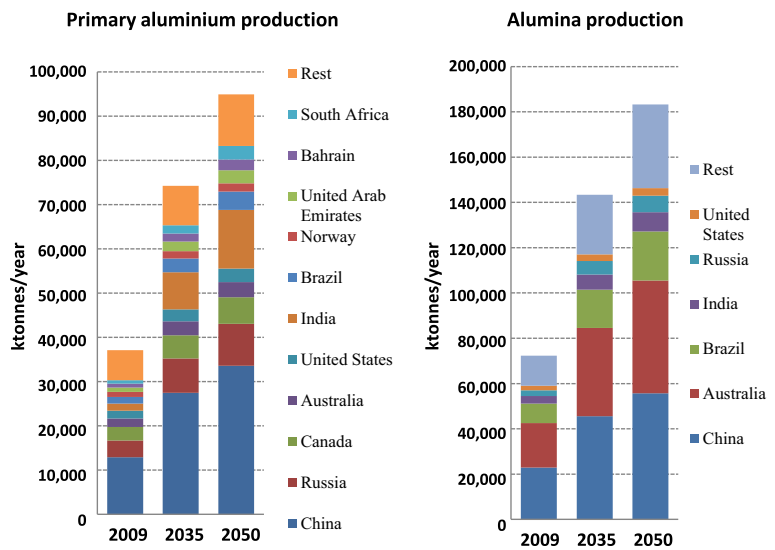
The construction of different scenarios will assist to identify the energy efficiency improvement and GHG reduction potentials under alternative energy development situations. For the scenario analysis in this study, two scenarios are constructed:

*Frozen efficiency scenario* According to the frozen efficiency scenario, the energy and GHG emission intensity for all processes will remain stable at the 2009 level. Any change in energy consumption and GHG emissions will be the result of changes in production.

*Business-as-usual (BAU) scenario* In the BAU scenario, energy efficiency improvements take place in all processes over the years, representing a continuation of past trends. The energy intensity decreases at the

<sup>11</sup> In 2009, Russian smelters produced 3.8 Mtonnes of aluminium. For an alumina requirement of 1.93 tonnes per tonne of aluminium, the alumina demand in Russian smelters was 7.4 Mtonnes. In 2009, Russian alumina refineries produced 2.8 Mtonnes of alumina. Assuming that all alumina produced was metallurgical, to satisfy the 2009 alumina demand in Russian smelters, about 4.5 Mtonnes alumina had to be imported.

**Fig. 3** Estimated future primary aluminium and alumina production in the major producing countries



historical rate of 0.4 % per year (based on IAI 2013c) in all processes except for aluminium smelting where a lower annual rate of energy efficiency improvement of 0.2 % is used. We use a lower energy efficiency improvement as a significant part of the past energy efficiency improvements was due to the shutting down of Söderberg cells. It is considered that all new capacity installed will have all energy efficiency measures implemented and will operate close to BPT levels. In this scenario, it is assumed that all new smelter capacity will use PFPB technology and all old Söderberg cells will be phased out by 2050. In addition, all new alumina refineries built in China and Russia will use the Bayer process. We assume that reductions in energy use due to stock retirement are included in the annual energy efficiency improvement.

6. *Identification of energy efficient technologies/measures.* The measures that can significantly contribute to a less energy and GHG emission intensive primary aluminium industry are identified and described in the “Review of energy efficiency improvements” section. The energy savings potentials and the associated investment costs are determined based on available information in literature.
7. *Implementation rates.* Where possible, the implementation rates of energy efficiency technologies/measures concerning alumina refining and aluminium smelting are based on information found in literature, industry reports and company Web sites. For example, for one of the energy efficiency

measures, tube digestion in alumina refining, the implementation rate was estimated based on information about the alumina plant capacity currently using tube digestion and on the alumina plant capacity that could adopt tube digestion (tube digestion can only be adopted by plants that use high-temperature digestion). For more details on how the implementation rates were estimated, please see Table 23 and Table 24 in the Appendix.

Where no information of the current level of implementation could be retrieved, the implementation rates were estimated based on the gap between the current energy use and the BPT energy use (see Table 21 in the Appendix) and expert knowledge from industry specialists. BPT refers to the most advanced technology that is in use at an industrial scale (IEA 2012). Table 23 and Table 24 in the Appendix show the estimated implementation rates.

In the case of anode manufacture, we use an implementation rate of 40 % for each measure, estimated based on the average energy use for anode baking and the BPT energy use, and we apply it only to the share of prebaked technology. Also, for ingot casting, we use the same implementation rate of 30 % for each measure, estimated again based on the average energy use for ingot casting and the BPT energy use.

8. *Construction of cost-supply curves.* The final step is the construction of the cost-supply curves based on Eqs. 1–3. Important variables that affect the profitability of each energy efficient technology/measure

in every country are the fuel and electricity costs. The bulk of fuel and electricity prices for industrial purposes were retrieved from the US Energy Information Administration (EIA) International Energy Statistics (2013b) and the IEA Key World Energy Statistics (IEA 2008) (see Table 5). As aluminium smelters are most usually situated close to low-cost electricity sources and alumina refineries close to bauxite sources, the price of electricity in alumina refineries and aluminium smelters differs. In this study, it is assumed that anode production and ingot casting plants are situated close to the smelter and have access to the same low-cost electricity. We assume that all prices remain stable throughout the 2009–2050 period. To assess the impact energy prices have on the results, we conduct a sensitivity analysis (see “Results and discussion” section).

## Review of energy efficiency improvements

In this section, all identified measures are briefly described. A summary can be seen in Table 6 and Table 7.

### Alumina refining

*Sweetening (1)* Gibbsite bauxite is characterized by higher solubility than boehmite bauxite at the same temperature. The addition of gibbsite at the downstream of the high temperature digester can significantly improve the alumina yield of processing boehmite (den Hond et al. 2007; Shah et al. 2004). Alumina yield is expected to increase by approximately 6 % (Shah et al. 2004) with no additional energy use. Den Hond et al. (2007) estimates alumina yield to increase by 6–10 g/L. The decrease in energy consumption due to the higher alumina yield is depicted in Table 6. The investment cost is estimated at \$8/tonne alumina (based on den Hond et al. 2007).

*Tube digestion with indirect preheating (2)* Replacing autoclaves with tube digesters will result in a significant decrease in energy use and CO<sub>2</sub> emissions. With indirect heating, the direct injection of steam in the bauxite slurry is avoided, resulting in more efficient utilization

of steam in other parts of the process and reduced energy use for evaporation. Energy savings will depend on the initial energy use and may range from 3 GJ/tonne alumina to up to 5.7 GJ/tonne alumina (Kunwar 2011; Suss et al. 2004). Switching from steam injection digestion to tube digestion will require the complete re-design and rebuilt of the digester (IPT/EC 2013). The investment cost for an integrated digestion and evaporation facility employing jacket pipe heaters is estimated at \$36–\$97/tonne alumina (based on HATCH 2011).

*High-rate thickening technology (3)* After sand separation, if required, the digestion discharge slurry passes through decanters for the separation of mud and green liquor. With the use of high-rate decanters, the liquor-to-mud contact time is reduced, reducing the reversion effect in which un-extracted bauxite in mud acts as seed for premature gibbsite crystallization. Alumina yield can improve by 1–2 g/L at an investment cost of 6\$/tonne alumina (den Hond et al. 2007).

*Seed filtration (4)* The introduction of seed filters drastically reduces the recycle of spent liquor, increases the precipitation fill A/C ratio, and the agglomeration capacity of fines. Alumina yield can increase by 5–10 g/L at an investment cost of \$14/tonne alumina (den Hond et al. 2007).

*Inter-stage cooling (5)* The introduction of as much as five inter-stage cooling steps will result in a closer to the optimum precipitation process. Alumina yield will increase by 2–5 g/L at an investment cost of \$5/tonne alumina (den Hond et al. 2007).

*Direct cooling (6)* In the heat interchange department (HID), green liquor going to precipitation is cooled by exchanging heat with the spent liquor leaving the precipitation and heading to digestion. Replacing indirect cooling using flash steam by direct cooling (i.e. heat exchangers) can enable digestion at higher caustic concentration and hence result in increased alumina yield. Alumina yield will increase by about 1–3 g/L at an investment cost of \$4/tonne alumina (den Hond et al. 2007).

*Stationary calciners (7)* Fluidized bed calcination (FBC) employs preheating and cooling with the use of several cyclone stages offering improved energy efficiency compared to rotary kilns

**Table 6** Energy efficiency improvements for alumina refining<sup>1</sup>

No	Measures	Electricity Savings (kWh/tonne alumina)	Fuel Savings (GJ/tonne alumina)	Investment Costs (\$/tonne alumina)	Change in O&M costs (\$/tonne alumina) <sup>2</sup>	Technical lifetime (years)
Digestion						
1	Sweetening	N/A	0.9	8	N/A	20
2	Tube digestion+indirect heating	–	4.4	66	N/A	20
Clarification						
3	High rate thickeners - HT Plants	N/A	0.2	6	N/A	20
	High rate thickeners - LT Plants	N/A	0.15	6	N/A	20
Precipitation						
4	Seed filtration - HT Plants	N/A	0.9	14	N/A	20
	Seed filtration - LT Plants	N/A	0.7	14	N/A	20
5	Inter-stage cooling - HT Plants	N/A	0.4	5	N/A	20
	Inter-stage cooling - LT Plants	N/A	0.35	5	N/A	20
Heat Interchange						
6	Direct cooling – HT Plants	N/A	0.3	4	N/A	20
	Direct cooling – LT Plants	N/A	0.2	4	N/A	20
Calcination						
7	Kiln retrofit	–	1.4	43	N/A	20
8	Optimized cyclone operation	3	0.2	0.1	N/A	20
9	“Hydrate-by-pass” system	–	0.1	3.3	N/A	20
10	Improved waste heat recovery	–	0.1	6.5	N/A	20
Overall process						
11	Advanced process control	14	0.6	3.0	N/A	10
12	Combined Bayer-Sinter→Bayer-flotation	N/A	10.4	160	+75	20
	Sinter→Bayer-flotation	N/A	22.0	230	–105	20
13	Combined Bayer-Sinter→Bayer	N/A	16.0	100	+60	20
	Sinter→Bayer	N/A	27.0	170	–110	20
	Bayer-flotation, Lime-Bayer→Bayer <sup>3</sup>	N/A	5.0	20	–60	20

<sup>1</sup> The energy savings each measure can achieve and the associated investment costs presented in this paper are only indicative. The actual energy efficiency improvements and investment costs are site-specific and should be carefully assessed prior to implementation

<sup>2</sup> These values exclude the change in energy costs. This is to avoid double counting when using Eqs. 1 and 2

<sup>3</sup> Since no information could be retrieved regarding the share of the Bayer-Flotation and the Lime-Bayer process on the overall Chinese alumina production, for this energy efficiency improvement measure we use the average investment and operational costs reported in the above paragraphs

(Missalla et al. 2011). Replacing rotary kilns with fluidized bed calciners will result in about 30 % energy savings (Missalla et al. 2011; Klett et al. 2011). Currently, all new plants prefer stationary calciners, such as circulating fluidized bed calciners or flash calciners. In 1995, 66 % of alumina was calcined in FBCs (IEA GHG 2000). Currently, the share of alumina produced in stationary calciners to the overall alumina production has increased to 80 % (Williams and Schmidt

2012). The investment cost is estimated at \$43/tonne alumina (based on IEA GHG 2000).

*Optimized cyclone operation (8)* Cyclones are widely used in the calcination of alumina for cooling and preheating. By improving the separation efficiency, fewer fines recirculate, resulting in improved heat recovery and lower pressure losses. Energy use for calcination can be reduced by 6 % (Dena 2010).

**Table 7** Energy efficiency improvements for aluminium smelting, anode production and ingot casting<sup>1</sup>

No	Measures	Electricity Savings (MWh/tonne aluminium)	Fuel Savings (%)	Fuel Savings (GJ/tonne aluminium)	Investment Cost (\$/tonne aluminium)	Technical lifetime (years)
Aluminium smelting						
13	VSS→PFPB	2.8	–	–	2,600	20
	HSS→PFPB	2.8	–	–	2,600	20
	SWPB→PFPB	0.8	–	–	620	20
	CWPB→PFPB	1.7	–	–	260	20
14	Optimize cell operation	2.0	–	–	240–410	20
Anode production and ingot casting <sup>2</sup>						
15	Optimum combustion air flow	–	5–25 %	0.2–0.8	2.2–3.0	10
16	Efficient operation of burners	–	5–10 %	0.2–0.3	1.6–2.0	10
17	Furnace pressure control	–	5–10 %	0.2–0.3	1.4–1.8	10
18	Furnace insulation	–	2–5 %	0.1–0.2	0.4–0.6	10
19	Waste heat recovery	–	10–30 %	0.3–1.0	8–12	20
20	Sensor and control systems	–	5–10 %	0.2–1.0	0.2–1.0	10
Motor driving equipment <sup>3</sup>						
21	Optimized motor system operation	0.1	–	–	7	10

<sup>1</sup> The energy savings each measure can achieve and the associated investment costs presented in this study are only indicative. The actual energy efficiency improvements and investment costs are site-specific and should be carefully assessed prior to implementation

<sup>2</sup> The energy savings for anode production and ingot casting are estimated based on the average energy use for anode production and ingot casting reported in the IAI data survey (IAI 2013a) and in BCS (2007)

<sup>3</sup> The electricity savings from improvements in motor systems also take into account electricity use in alumina refineries

The investment cost is estimated at \$0.1/tonne alumina (based on Dena 2010).

*“Hydrate by-pass” system (9)* With the installation of a hydrate by-pass system, a part of alumina hydrate (up to 15 %) can “by-pass” the calciner and enter a pot where it is calcined by the hot alumina leaving the calciner. In this way, a part of alumina hydrate is directly calcined by the increased temperature of the produced alumina. Energy use will decrease by 3–5 % (Missalla et al. 2011). Information on the required investment cost could not be found. It is assumed that the investment cost required is half the cost required for the “improved waste heat recovery” measure, \$3.3/tonne alumina.

*Improved waste heat recovery (10)* Waste heat recovery in a stationary kiln employing several cyclone stages and a hydrate by-pass system can be further improved. For example, heat from the cooler can be used to dry moist hydrate prior to its entrance to the first preheating stage. As the drying heat requirements are now lower, more preheater stages could be added to utilize heat

from the calciner off-gases. Energy savings for a calciner already utilizing a hydrate by-pass system are estimated at 3 % (Klett et al. 2011). The investment cost is estimated at \$6.5/tonne alumina.

*Improved process control (11)* The Bayer process is composed of highly interactive processes with long dead times. Advanced control of the whole alumina refining process will result in increased yield throughput and lower energy use. Fuel use due to improved efficiency and higher throughput is estimated to decrease by 5 % while electricity use is also expected to decrease by the same amount. Investment costs are estimated at \$3/tonne alumina (based on Sidrak 2001).

*Switch from the alternative processes to the Bayer process (low-temperature digestion) (12)* Importing better quality bauxite in countries such as China and Russia would eliminate the use of the more energy-intensive combined Bayer-Sinter, Sinter, Bayer-Flotation and Lime-Bayer processes. Replacing the Sinter process would decrease the energy use by 27 GJ/tonne alumina

(based on energy use of 38 GJ/t for the Sinter process and 10 GJ/t for the Bayer process with low-temperature digestion). Replacing the combined Bayer-Sinter process with the Bayer will reduce the energy use by about 16 GJ/tonne alumina; alumina production with the combined Bayer-Sinter process consumes in Russia about 27 GJ/t alumina (Liu et al. 2010) and in China about 26 GJ/t alumina (Li et al. 2008).

The investment costs for switching from the combined Bayer-Sinter to the Bayer process will amount to \$100/tonne while operational costs (excluding the impact of lower energy use) are expected to increase by about \$60/tonne alumina, primarily due to the increased costs from importing better quality bauxite and the additional caustic soda requirements. Switching from the Sinter to the Bayer process will require an investment of \$170/tonne alumina. Although bauxite and caustic soda consumption will increase, operational costs (excl. energy use) are expected to decrease by about \$110/tonne alumina due to lower limestone requirements and the elimination of soda ash needs.

In addition, replacing the Bayer-Flotation and Lime-Bayer processes with the Bayer process will require an investment of about \$20/tonne alumina. Switching from the Bayer-Flotation to the Bayer process will decrease operational costs (excl. energy use) by \$10/tonne alumina as improved material use will more than compensate the increased bauxite costs. Switching from the Bayer-Flotation to the Bayer process will lower operational costs by \$110/tonne alumina mainly due to the lower limestone use.

*Switch from the alternative processes to the Flotation-Bayer (13)* When better quality bauxite cannot be obtained, the combined Bayer-Sinter and the Sinter processes could potentially be replaced by a less energy-intensive process that composes a variation of the Bayer process, the Flotation-Bayer process. Energy use could decrease by about 10 GJ/tonne when replacing the combined Bayer-Sinter process and by 22 GJ/tonne when replacing the Sinter process (for an energy use of the Bayer-Flotation process of 16 GJ/tonne).

When replacing the combined Bayer-Sinter process, the investment costs required will amount to \$160/tonne alumina while the operational costs are expected to increase by about \$75/tonne alumina

due to increased bauxite and caustic soda costs. For the replacement of the Sinter process, the investment costs will be about \$230/tonne while operational costs are expected to decrease by about \$105/tonne due to the elimination of soda ash.

## Aluminium smelting

*Conversion to PFPB technology cells (14)* The conversion of the CWPB, SWPB and the outdated Söderberg cells to state-of-the-art PFPB technology will have major energy and environmental benefits. Upgraded PFPB plants have an energy use of 13.8 MWh/tonne while greenfield PFPB plants are characterized by an even lower energy use of 13.4 MWh/tonne aluminium (Schwarz et al. 2001). The energy savings will depend on the technology substituted and will range from about 5–20 % while PFC emissions can decrease by up to 93 % (see Table 4). The investment cost required will range from \$260 to 620 for switching from SWPB and CWPB to PFPB cells. For switching from the Söderberg technology cells to PFPB, the investment is substantial, estimated at \$2,600/tonne aluminium (see Table 7) (Harnisch et al. 1998).<sup>12</sup>

*Optimize cell operation (15)* With the further improvement of pot control and point-feeding systems in existing PFPB cells, the occurrence of anode effects can be reduced, while the electrolytic bath will be better controlled resulting in more optimal operating conditions (BCS 2007). The electricity use can decrease by about 0.2 MWh/tonne aluminium, while the investment cost will range between 100 and 150 Euros/tonne aluminium (Schwarz 2008). It is common, when such cell renovations are conducted, to also increase the cell amperage and anode size and implement new cathodes (Morrey 2001 as found in Schwarz 2008). Due to the lack of data on investments to renovate PFPB cells, we assume investment costs twice the investment cost reported by Schwartz (2008) for optimizing pot control. The renovation of current PFPB cells can decrease the electricity use by 15 %.

<sup>12</sup> In this study, to adjust the investment costs from older years to current years, we used the Chemical Engineering Plant Cost Index (CEPCI).



## Anode production and ingot casting

Energy consumption for anode manufacture and ingot casting can be reduced with the improvement of the process heating systems, i.e. through the optimization of the combustion process, heat containment, heat transfer, waste heat recovery and improved process control (U.S. DOE 2004). The associated investment costs of energy efficiency improvements were estimated based on the average payback period (PBP) reported in the Industrial Assessment Centers (IAC) Database for all US manufacturing industries and the typical energy costs. As the PBP depends on energy prices and the US natural gas prices have experienced great fluctuation within the period 2000–2013, in the case of heat savings, the average PBP of a specific year was taken into consideration and not the average PBP of all years.

*Optimum combustion air flow (16)* The efficiency of the combustion process can increase with the use of the optimum amount of excess air, resulting in the use of the appropriate air-to-fuel ratio. The energy savings range between 5 and 25 % (U.S. DOE 2004). For an average PBP of 0.9 years reported for 2011 (IAC 2013) in US industries and 15 % average energy savings, the investment cost is estimated at \$2.2–3.0 per tonne aluminium ingot.

*Adjust burners for efficient operation (17)* The use of proper burners can increase the amount of heat transferred to the load increasing productivity and reducing fuel requirements. Improving heat transfer in furnaces will result in 5–10 % energy savings (U.S. DOE 2004). For an average PBP of 1 year reported for 2011 (IAC 2013) in US industries and 8 % average energy savings, the investment cost is estimated at \$1.6–2.0 per tonne aluminium ingot.

*Furnace pressure control (18)* Fixing the leaks and installing or correctly operating pressure control will result in 5–10 % energy savings (U.S. DOE 2004). In this way, heat losses due to air infiltration often observed when furnaces are operated at negative pressures can be avoided. For an average PBP of 0.9 years reported for 2011 (IAC 2013) in US industries and 8 % average energy savings, the

investment cost is estimated at \$1.4–1.8 per tonne aluminium ingot.

*Use insulation in furnaces to facilitate heating/cooling (19)* The use of insulating materials reduces heat losses to the environment through convection and conduction. The energy savings are in the range of 2–5 % (U.S. DOE 2004). For an average PBP of 0.3 years reported for 2009 (IAC 2013) in US industries and 4 % average energy savings, the investment cost is estimated at \$0.4–0.6 per tonne aluminium ingot.

*Use waste heat from hot flue gases to preheat combustion air (20)* With the recovery of the heat of exhaust gases to preheat the combustion air, the heat losses decrease while also less fuel is required to reach the necessary process temperature. The energy savings range between 10 and 30 % (U.S. DOE 2004). For an average of 1.7 years for 2009 (IAC 2013) and 20 % average energy savings, the investment is estimated at \$8–12/tonne aluminium ingot.

*Improved sensor and control systems (21)* Control systems can be improved to reduce energy losses especially when the system operates at low throughput (U.S. DOE 2004). Energy savings are estimated at 5–10 % with a typical PBP of 0.1–0.5 years (Thekdi 2000). The investment cost is estimated at \$0.2–1.0 per tonne aluminium ingot.

## Machine driving systems

*Optimized operation of motor systems (22)* According to the IAI survey (2013a), in 2010, about 15.6 MWh/tonne of electricity was needed to produce 1 tonne of aluminium. About 15.3 MWh/tonne aluminium (98 % of overall electricity use) was consumed in electrolysis and the remaining in alumina refining, anode production and ingot casting. Less than 7 % of the electricity used in electrolysis, about 1 MWh/tonne of aluminium (IAI 2013c; Covec 2009), is used in auxiliary equipment and rectifiers. Rectification losses account for about 2 % of electricity use (Covec 2009).

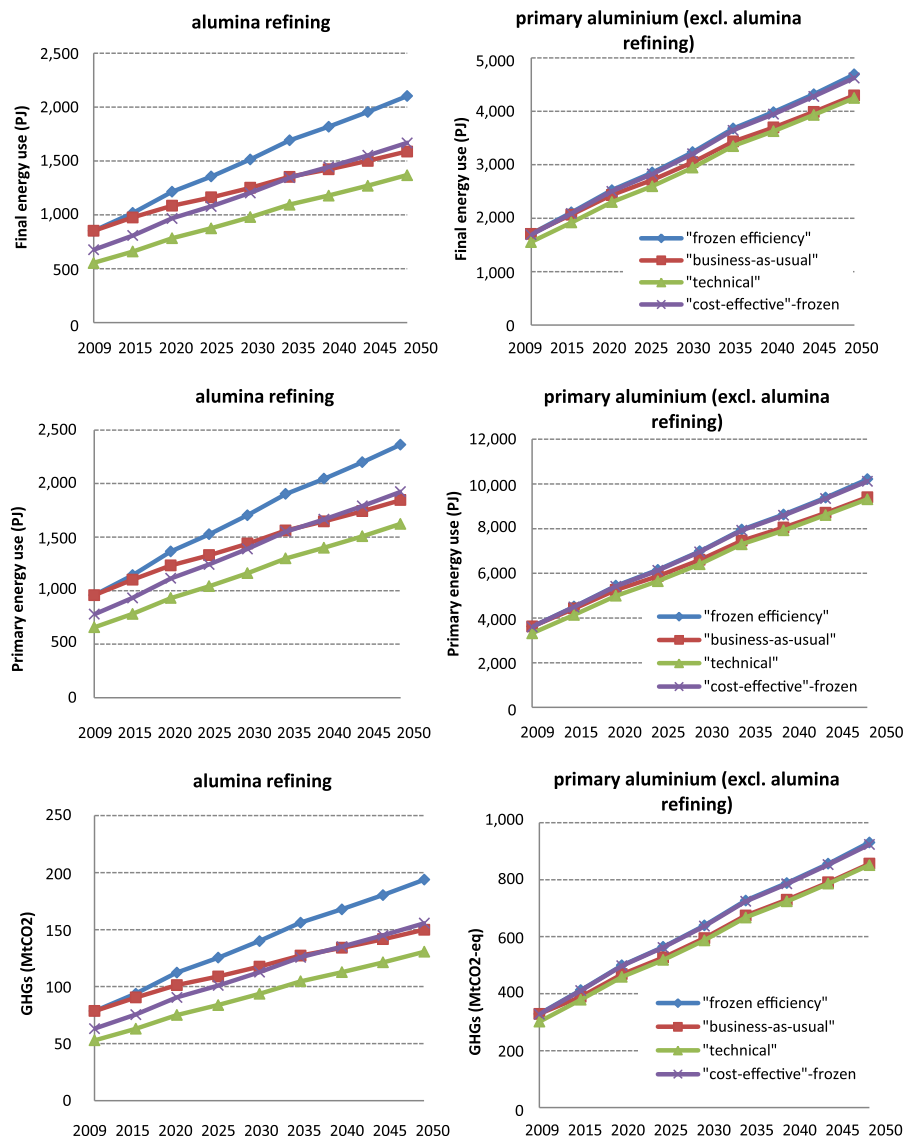
Based on the 2010 Manufacturing Energy Consumption Survey (MECS) (EIA 2013c), in 2010, about 60 % of the electricity consumed in other than the electrochemical process in the US primary aluminium industry, was used for machine

drives. Energy use in motor systems can be reduced by 15 % through motor upgrading and system level efficiency measures, i.e. correct motor sizing, employ ASDs, improve the energy efficiency of pump, fan and air compressor systems (U.S. DOE 2002). Hence, we estimate that energy efficiency improvements for machine driving equipment can decrease electricity use by about 0.1 MWh/tonne aluminium. The investment cost is estimated based on the average PBP of 1.1 years for all US industries as reported in the IAC (2013) at \$7/tonne aluminium.

## Results and discussion

Figure 4 depicts the energy use and GHG emissions under the frozen efficiency and the BAU scenarios and the energy use when all energy savings measures identified in this study are applied without taking economic considerations into account (“technical”), and the energy use when only cost-effective measures are adopted (“cost-effective”) under the frozen efficiency scenario.

Under the frozen efficiency scenario, the primary energy use in alumina refining (top 6 alumina-producing countries) will increase from 957 PJ in 2009 to about 2,360 PJ



**Fig. 4** Energy use and GHG emission development under different scenarios (discount rate=30 %)

in 2050, an increase of 147 %. Similarly, GHG emissions from alumina refining, primarily from fuel combustion, will increase from about 80 MtCO<sub>2</sub> in 2009 to 194 MtCO<sub>2</sub> in 2050. Under the BAU scenario, the increase in both primary energy use and GHG emissions is less drastic with primary energy use and GHG emissions reaching about 1,845 PJ and 150 MtCO<sub>2</sub> by 2050, respectively. There is the technical potential to limit the energy use by 31 % when compared to the frozen efficiency scenario and 12 % when compared to the BAU scenario. The cost-effective potential for reducing the energy and GHG emissions is estimated at 19 and 20 % when compared to the frozen efficiency scenario, respectively.

The primary energy use for primary aluminium production (excl. alumina refining) (top 11 primary aluminium-producing countries) under the frozen

efficiency scenario is expected to increase from about 3,600 PJ in 2009 to 10,200 PJ in 2050, an increase of more than 180 %. The GHG emissions will show a similar increase, increasing from about 330 MtCO<sub>2-eq.</sub> in 2009 to 930 MtCO<sub>2-eq.</sub> in 2050. In the BAU scenario, the increase in energy use remains substantial; the 2050 primary energy use is estimated at 9,400 PJ and the GHG emissions at 856 MtCO<sub>2-eq.</sub>. The technical potential for reducing the primary energy use and GHG emissions is 9 % when compared to the frozen efficiency scenario, while when in comparison to the BAU scenario, the remaining technical potential is low, estimated at 0.9 and 0.6 %, respectively. The cost-effective primary energy and GHG savings potentials when in comparison to the frozen efficiency scenario are 0.9 and 0.8 %, respectively.

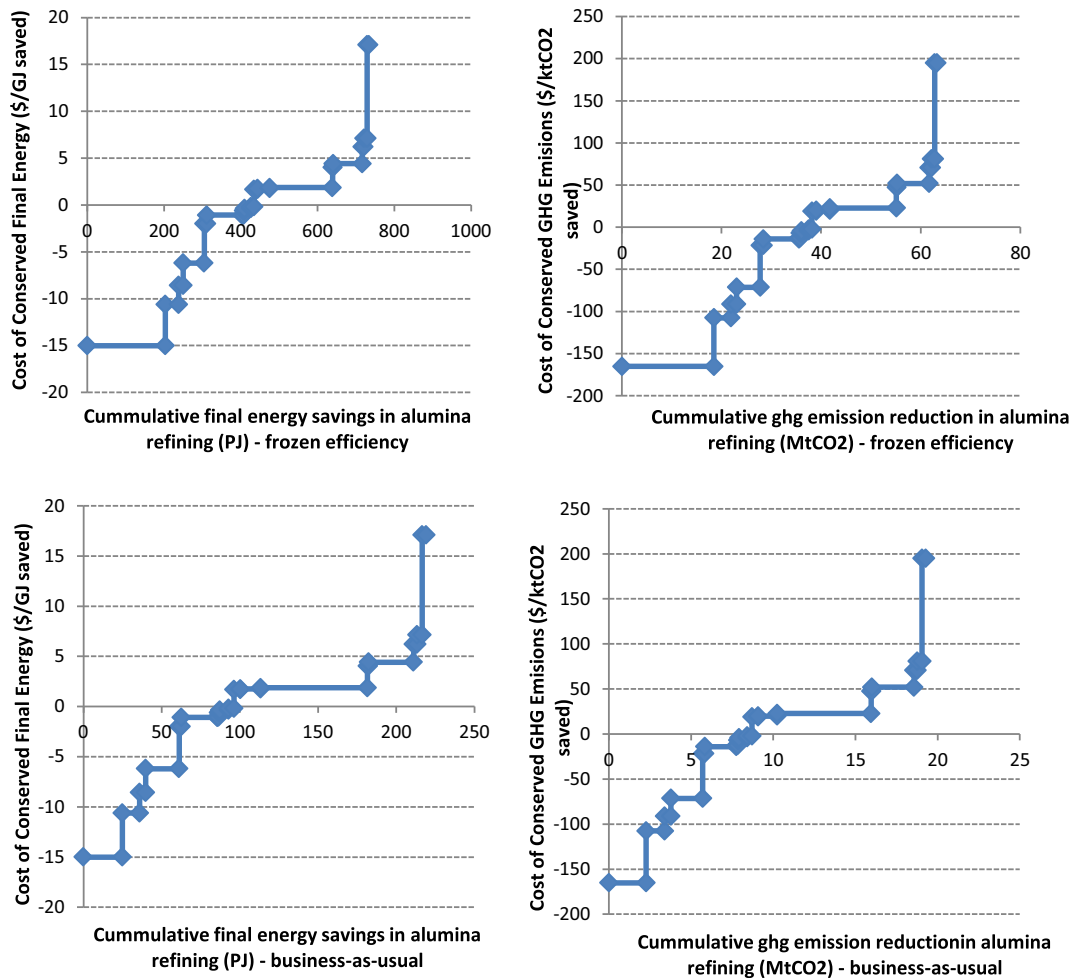


Fig. 5 Energy and GHG abatement curves for the alumina refining industry (year 2050; discount rate=30 %)

**Table 8** Energy efficiency measures for the alumina refining industry ranked based on their  $CCE_{final}$  (discount rate=30 %)

Efficiency measures	"Frozen-efficiency"				"Business-as-usual"				Associated costs		
	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO <sub>2</sub> )	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO <sub>2</sub> )	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO <sub>2</sub> )	Cost of conserving final energy (\$/GJ)	Cost of mitigating GHGs (\$/ktCO <sub>2</sub> )
Bayer-flotation, Lime-Bayer→Bayer	203	203	18.5	25	25	2.3	25	25	2.3	-15.0	-165
Advanced control	35	39	3.4	11	13	1.1	11	13	1.1	-10.6	-107
Optimized cyclone operation	12	13	1.1	4	4	0.4	4	4	0.4	-8.6	-91
Sinter→Bayer	55	55	4.7	21	21	1.9	21	21	1.9	-6.2	-71
Sweetening	7	7	0.6	2	2	0.1	2	2	0.1	-2.0	-22
Tube digestion+indirect heating	93	93	7.1	23	24	1.9	23	24	1.9	-1.1	-14
Inter-stage cooling - HT Plants	3	3	0.3	1	1	0.1	1	1	0.1	-1.1	-13
Direct cooling - HT Plants	3	3	0.2	1	1	0.1	1	1	0.1	-0.6	-7
Inter-stage cooling - LT Plants	17	17	1.5	6	6	0.5	6	6	0.5	-0.4	-4
Seed filtration - HT Plants	8	8	0.6	3	3	0.3	3	3	0.3	-0.2	-2
<b>Total "cost-effective"</b>	<b>435</b>	<b>440</b>	<b>38.2</b>	<b>96</b>	<b>99</b>	<b>8.7</b>	<b>96</b>	<b>99</b>	<b>8.7</b>		
Direct cooling - LT Plants	10	10	0.8	4	4	0.4	4	4	0.4	1.7	19
Seed filtration - LT Plants	31	31	2.8	13	13	1.2	13	13	1.2	1.8	20
Combined Bayer-Sinter→Bayer	164	164	13.3	68	68	5.7	68	68	5.7	1.9	23
High rate thickeners - HT Plants	2	2	0.1	1	1	0.1	1	1	0.1	4.0	47
Kiln retrofit	76	76	6.5	29	29	2.6	29	29	2.6	4.4	52
"Hydrate-by-pass" system	5	5	0.4	2	2	0.2	2	2	0.2	6.2	71
High rate thickeners - LT Plants	7	7	0.6	3	3	0.3	3	3	0.3	7.1	81
Improved waste heat recovery	5	5	0.4	3	3	0.2	3	3	0.2	17.1	195
<b>Total "technical"</b>	<b>734</b>	<b>740</b>	<b>63.3</b>	<b>219</b>	<b>222</b>	<b>19.3</b>	<b>219</b>	<b>222</b>	<b>19.3</b>		

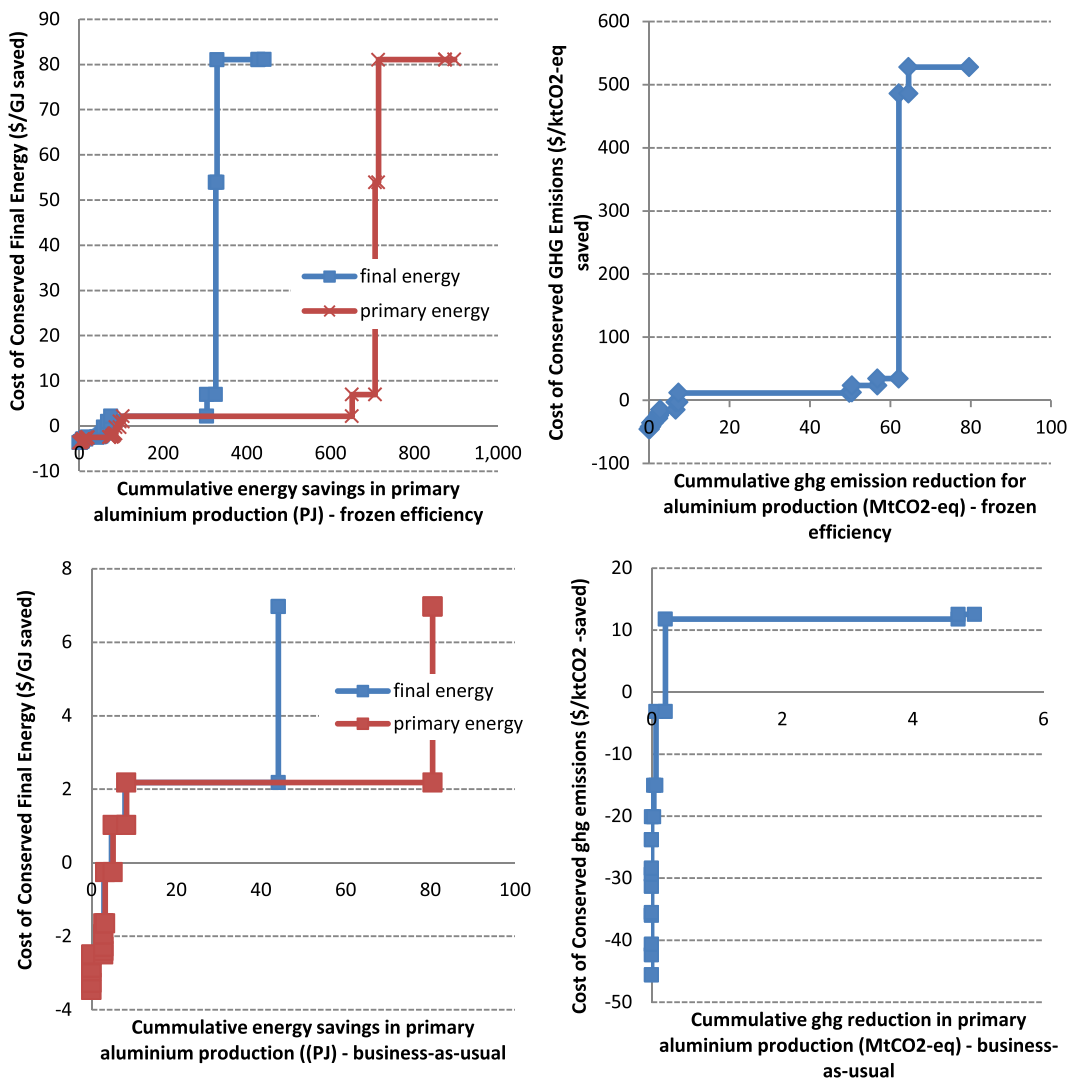
Cost-supply curves

Figure 5 shows the cost-supply curves for alumina refining under the frozen efficiency and the BAU scenarios. As shown in more detail in Table 8, 10 out of the 18 energy efficiency improvement measures are cost-effective, as their CCE is less than 0.

Table 8 shows all the energy efficiency improvement measures for alumina refining assessed in this study, along with their contribution to the total technical and cost-effective energy and GHG savings potentials. Under the frozen efficiency scenario, the cost-effective energy and GHG savings potential is 435 PJ (59 % of

the technical potential) and about 38 MtCO<sub>2</sub>, respectively. Measures with the highest impact are the replacement of alternative options for alumina refining that currently operate in China and Russia, tube digestion and kiln retrofitting. Assuming that China and Russia can obtain better quality bauxite and therefore adopt the Bayer process, about 422 and 115 PJ could be saved under the frozen efficiency and the BAU scenarios, respectively.

The energy savings potentials under the BAU are lower as new capacities installed have already adopted the measures and old capacity improved annually by 0.4 %. To account for the improvement in old stock, it is



**Fig. 6** Energy and GHG abatement curves for the primary aluminium industry (year 2050; excluding alumina refineries) (discount rate= 30 %)

**Table 9** Energy efficiency measures for the primary aluminium production ranked based on their  $CCE_{final}$  (discount rate = 30 %)

Efficiency measures	“frozen-efficiency”			“business-as-usual”			Associated costs		
	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO <sub>2</sub> )	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO <sub>2</sub> )	Cost of conserving final energy (\$/GJ)	Cost of mitigating GHGs (\$/ktCO <sub>2</sub> )	
Sensor and control systems_ingot	3.5	3.5	0.3	0.0	0.0	0.0	-3.7	-46	
Sensor and control systems_anodes	3.0	3.0	0.2	0.0	0.0	0.0	-3.5	-42	
Furnace insulation_ingot	1.6	1.6	0.1	0.0	0.0	0.0	-3.3	-41	
Furnace insulation_anodes	1.4	1.4	0.1	0.0	0.0	0.0	-2.9	-36	
Optimum combustion air flow_ingot	7.0	7.0	0.6	0.0	0.0	0.0	-2.9	-36	
Furnace pressure control_ingot	3.5	3.5	0.3	0.0	0.0	0.0	-2.5	-31	
Optimize motor system operation	22.9	51.6	3.8	2.5	2.8	0.0	-2.5	-15	
Optimum combustion air flow_anodes	6.0	6.0	0.5	0.0	0.0	0.0	-2.4	-29	
Efficient operation of burners_ingot	3.5	3.5	0.3	0.0	0.0	0.0	-2.3	-28	
Furnace pressure control_anodes	3.0	3.0	0.2	0.0	0.0	0.0	-2.0	-24	
Efficient operation of burners_anodes	3.0	3.0	0.2	0.4	0.4	0.0	-1.7	-20	
Waste heat recovery_ingot	9.4	9.4	0.8	1.8	1.8	0.1	-0.3	-3	
<b>Total “cost-effective”</b>	<b>67.8</b>	<b>96.5</b>	<b>7.4</b>	<b>4.7</b>	<b>5.1</b>	<b>0.2</b>			
Waste heat recovery_anodes	8.0	8.0	0.7	3.2	3.2	0.3	1.0	13	
Optimized cell operation	228.8	546.8	42.5	36.2	72.3	4.5	2.2	12	
CWPPB → PFPB	21.2	55.2	6.3	0.0	0.0	0.0	7.0	24	
SWPBB → PFPB	3.4	8.1	5.3	0.0	0.0	0.0	54.0	34	
VSS → PFPB	98.5	159.8	15.1	0.0	0.0	0.0	81.1	528	
HSS → PFPB	14.6	21.9	2.4	0.0	0.0	0.0	81.1	486	
<b>Total “technical”</b>	<b>442.2</b>	<b>896.2</b>	<b>79.7</b>	<b>44.1</b>	<b>80.5</b>	<b>5.0</b>			

assumed that the measures with the lowest CCE in each country have been adopted. Under the BAU scenario, it is assumed that all new alumina capacity installed in China and Russia uses the Bayer process.

In practice, the cost-effectiveness of the measures does not only depend on the change in energy expenditures. For example, all measures that improve the alumina refineries' yield, when adopted for capacity purposes, will lower the refinery's fixed costs and increase certain process efficiencies. These measures, even if they may not be justifiable based only on their energy conserving capabilities, from an overall economics point of view, they might be cost-effective.

To assess the potential for energy savings under a scenario in which Russia and China keep on processing local bauxite with a lower than the average bauxite quality, the efficiency measures “combined Bayer-Sinter→Bayer” and the “Sinter→Bayer” are replaced by the “combined Bayer-Sinter→Flotation-Bayer” and the “Sinter→Flotation Bayer”, while the measure “Bayer-Flotation, Lime-Bayer→Bayer” is not taken into consideration. In this scenario, the total technical potential for energy savings under the frozen efficiency and the BAU scenarios are 463 and 94 PJ, respectively. For more information on the absolute energy savings and the cost-effectiveness of each measure in this scenario, see Fig. 8 and Table 25 in the Appendix.

Figure 6 shows the energy and GHG abatement curves for the primary aluminium industry (excluding alumina refining). Under the frozen efficiency scenario, most of the energy savings are identified as non-cost-effective (CCE higher than 0). As in the BAU scenario, it is assumed that Söderberg cells will be phased out by

2050, these measures do not contribute to the energy savings potential.

Table 9 presents the contribution of each measure to the overall savings potential. Under the frozen efficiency scenario, about 896 PJ of primary energy can be saved. Under the BAU scenario, however, the energy savings potential is significantly lower, as most of the energy savings potential identified in the frozen efficiency scenario has been implemented. This is primarily due to the assumptions used for the construction of the BAU scenario; the phasing out of Söderberg cells by 2050, the adoption of all energy efficiency measures in new installed aluminium capacity and the 0.2 % energy efficiency improvement in old capacity. About 15 % of the final energy savings, 11 % of the primary energy savings and 9 % of the GHG emissions savings are cost-effective under the frozen efficiency scenario, while under the BAU scenario, the percentages are 11, 6 and 4 %, respectively.

The technical potential would have been higher if innovative measures were also taken into consideration. New technologies currently being researched such as wetted drained cathodes and inert anodes can substantially improve the efficiency of the Hall Heroult process, while other new technologies such as carbothermic reduction and kaolinite reduction can be used to replace the Heroult process.

In Tables 10 and 11, the energy savings and GHG savings potentials can be seen identified in the top 6 alumina and top 11 primary aluminium-producing countries. Notice that the total cost-effective savings potentials appearing in Tables 10 and 11 differ from the total cost-effective savings potentials in Tables 8 and 9. This

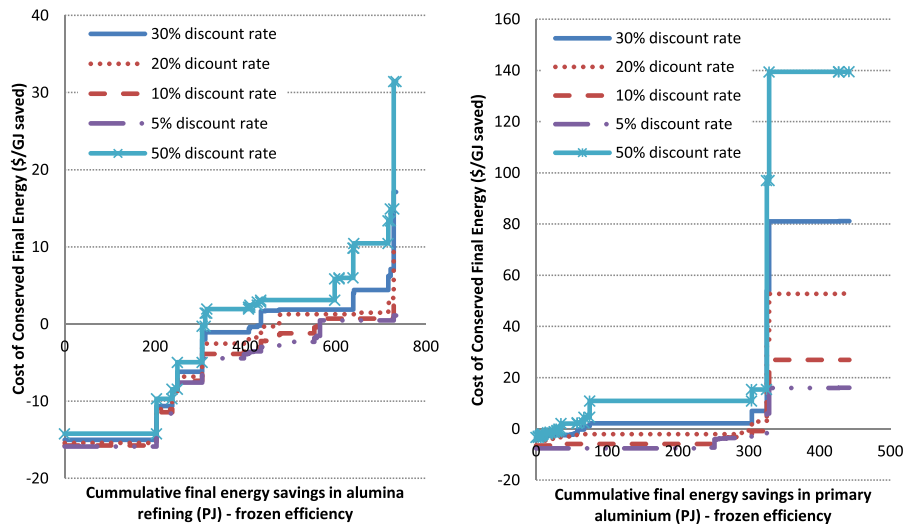
**Table 10** Energy and GHG savings potentials in alumina refining per country (discount rate=30 %)

Countries	2050 alumina production (Mtonnes)	Final energy savings (PJ)				GHG savings (MtCO <sub>2</sub> )			
		frozen efficiency		BAU		frozen efficiency		BAU	
		cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical
China	56	285	527	64	178	26.3	48.2	5.9	16.3
Russia	4	10	83	0	25	0.7	5.6	0.0	1.7
Australia	50	54	64	0	1	3.8	4.6	0.0	0.1
United States	3	15	16	8	9	0.8	0.9	0.4	0.5
India	8	21	32	2	7	2.0	3.0	0.2	0.7
Brazil	22	5	12	0	0	0.4	0.9	0.0	0.0
<b>Total</b>	<b>143</b>	<b>390</b>	<b>734</b>	<b>73</b>	<b>219</b>	<b>34.0</b>	<b>63.3</b>	<b>6.6</b>	<b>19.3</b>

**Table 11** Energy and GHG savings potentials for primary aluminium production (excl. alumina refining) per country (discount rate=30 %)

Countries	2050 primary aluminium production (Mtonnes)	Final energy savings (PJ)				Primary energy savings (PJ)				GHG savings (MtCO <sub>2</sub> -eq.)			
		frozen efficiency		BAU		frozen efficiency		BAU		frozen efficiency		BAU	
		cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical
China	34	134	139	7	9	331	339	17	19	30.2	33.3	1.6	1.7
Russia	10	3	69	0	5	3	92	0	7	0.2	7.1	0.0	0.0
Australia	3	2	31	0	5	2	77	0	11	0.2	8.2	0.0	1.0
United States	3	3	22	0	7	4	44	0	16	0.2	4.0	0.0	1.2
India	13	11	77	0	4	15	168	0	8	1.2	14.8	0.0	0.6
Brazil	4	2	32	0	1	2	34	0	1	0.2	1.9	0.0	0.0
Canada	6	3	32	0	11	3	32	0	11	0.2	1.6	0.0	0.0
Norway	2	1	2	0	1	1	2	0	1	0.1	0.2	0.0	0.0
United Arab Emirates	3	0	12	0	1	0	34	0	1	0.0	2.1	0.0	0.1
Bahrain	2	0	10	0	0	0	30	0	1	0.0	1.9	0.0	0.1
South Africa	3	1	16	0	1	1	44	0	4	0.1	4.6	0.0	0.4
<b>Total</b>	<b>83</b>	<b>162</b>	<b>442</b>	<b>8</b>	<b>44</b>	<b>363</b>	<b>896</b>	<b>19</b>	<b>81</b>	<b>33</b>	<b>80</b>	<b>1.7</b>	<b>5.0</b>





**Fig. 7** Energy abatement curves for the alumina refining and the primary aluminium (excluding alumina refineries) industries for varying discount rates

is because the CCE shown in Tables 8 and 9 is the weighted average CCE. However, due to different energy prices, the CCE will be different in each country and measures that might be cost-effective in one country might not be cost-effective in another.

The highest potential for energy savings in the alumina refining industry appears in China and Russia, 83 % of the total technical energy savings potential, as these two countries currently use energy-intensive alternative to the Bayer processes to produce alumina. China alone accounts for 72 % of the technical energy savings potential under the frozen efficiency scenario due to its large alumina production and the high-energy savings potential there is from switching to the Bayer process. However, if China and Russia keep processing local bauxite, the switch from the alternative alumina refining processes to the Bayer-flotation process instead of the switch to the Bayer process will lower the technical potential for energy savings to 281 PJ in China and 58 PJ in Russia.

The cost-effective savings potentials shown in Table 11 are significantly higher than in Table 9 because the “optimized cell operation” measure is found to be cost-effective in China. The highest potential for energy savings in the primary aluminium industry (excluding alumina refining) under the frozen efficiency scenario appears in China, 31 % of the total technical energy savings potential and then follows India with 17 %. Improvements in primary aluminium production can decrease total GHG emissions by 80 MtCO<sub>2-eq.</sub>, 80 %

of which can take place in China, Russia, India and Australia.

Technologies that are found cost-effective across all countries are “advanced control” and “optimized cyclone operation” while almost all measures concerning improvements in anode baking and ingot casting are also considered cost-effective. In the case of aluminium smelting and for a 30 % discount rate, all measures are found to be non-cost-effective in all countries except in China, the country with the highest electricity prices, where “optimized cell operation” is found to be cost-effective.

It is important to note that in this analysis, the adoption of energy efficiency measures in countries that use electricity produced from renewable sources (e.g. hydropower) for aluminium smelting such as Brazil, Canada and Norway will not result in as high primary energy and GHG savings as in countries producing electricity from fossil fuels.<sup>13</sup>

For a number of countries that use large amounts of hydropower for aluminium smelting, using the average country mix for the generation of electricity will result in higher primary energy savings and GHG abatement potential (see Table 26 in the Appendix) than the potentials shown in Table 11. Using the average country fuel

<sup>13</sup> Although in this analysis we have considered a near-zero emission factor for hydropower for every country, in reality, GHG emissions can vary substantially per country as tropical reservoirs were shown to be non-negligible GHG emitters (1,300–3,000 kgCO<sub>2-eq.</sub>/MWh) (Steinhurst et al. 2012).

**Table 12** Cost-effective final energy savings potentials under the frozen efficiency scenario for varying discount rates

Discount rates	Alumina refining			Primary aluminium (excl. alumina refining)		
	cost-effective (PJ)	non-cost-effective (PJ)	share of cost-effective on the overall technical potential	cost-effective (PJ)	non-cost-effective (PJ)	share of cost-effective on the overall technical potential
50 %	312	423	42 %	36	384	8 %
30 %	435	300	59 %	68	374	15 %
20 %	475	259	65 %	305	138	69 %
10 %	565	169	77 %	326	116	74 %
5 %	565	169	77 %	326	116	74 %

mix for electricity generation will result in about 1,100 PJ total primary energy savings and 97 MtCO<sub>2-eq</sub> emission reduction potentials under the frozen efficiency scenario.

#### Sensitivity analysis

To assess the cost-effective potentials presented above, we performed a sensitivity analysis and calculated the cost-supply curves for varying discount rates and energy prices.

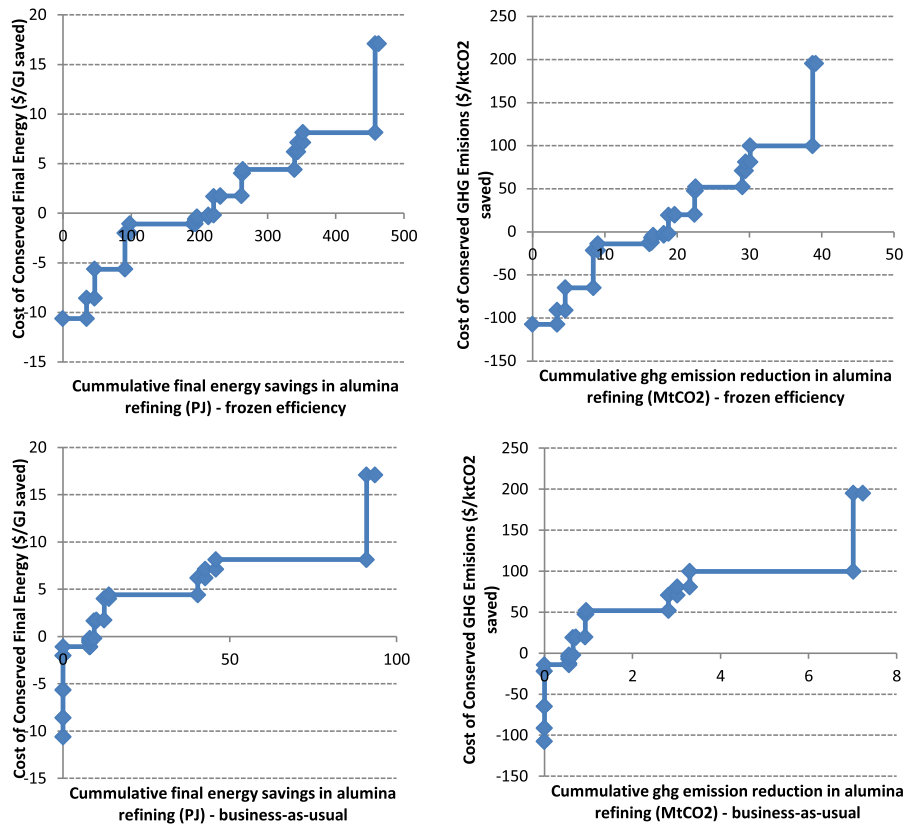
In energy models, the discount rate can be used to demonstrate the hurdles to adopting energy efficiency measures. In this analysis, a high discount rate of 30 % is used. By decreasing the discount rate, the CCE of each energy efficiency measure decreases, increasing the cost-effective savings potential. The opposite happens when the discount rate increases, limiting in this way the cost-effective savings potential. Figure 7 shows the energy conservation curves for different discount rates.

The use of a lower discount rate will decrease the CCE of each measure shifting the cost-supply curves vertically downwards as shown in Fig. 7. Table 12 shows the impact of a lower and a higher discount rate on the cost-effective energy savings potentials.

In this analysis, the energy prices used in the calculations were assumed to remain stable through the years. The fluctuation, however, of energy prices will affect the cost-effectiveness of every energy efficiency improvement measure. Table 13 shows the cost-effective savings potentials for higher and lower energy prices while maintaining all other parameters such as the discount rate and the investment costs stable. It is shown that for 30 % higher energy prices, there will be a significant increase in the cost-effective energy savings potentials in primary aluminium production with the measure “*Optimized cell operation*” becoming cost-effective. On the other hand, a decrease in energy prices can substantially decrease the cost-effectiveness of

**Table 13** Cost-effective final energy savings potentials under the frozen efficiency scenario for varying energy prices

Change in energy prices	Alumina refining			Primary aluminium (excl. alumina refining)		
	cost-effective (PJ)	non-cost-effective (PJ)	share of cost-effective on the overall technical potential	cost-effective (PJ)	non-cost-effective (PJ)	share of cost-effective on the overall technical potential
+50 %	639	95	87 %	305	138	69 %
+30 %	435	300	59 %	305	138	69 %
+15 %	435	300	59 %	68	374	15 %
<i>current prices</i>	<i>435</i>	<i>300</i>	<i>59 %</i>	<i>68</i>	<i>374</i>	<i>15 %</i>
-15 %	408	326	56 %	58	384	13 %
-30 %	312	423	42 %	36	384	8 %
-50 %	305	430	41 %	30	390	7 %



**Fig. 8** Energy and GHG abatement curves for the alumina refining industry (discount rate=30 %)-(switch alternative processes used in China and Russia to the Bayer-flotation instead of the Bayer)

measures. For example, a decrease in energy prices by 15 and 30 % will decrease the cost-effective energy savings potential for the alumina refining industry by 6 and 28 %, respectively.

Another parameter that can highly influence the cost-effectiveness of the measures is the investment cost of the technologies. A higher future investment cost will decrease the identified cost-effective energy savings potentials while the opposite is true for lower future investment costs. In this analysis, the investment costs were assumed to remain constant throughout the 2009–2050 period as it is hard to estimate whether capital costs will increase due to for example higher inflation rates, or go down due to a high learning-rate.

When compared to Kermeli et al. (2014), the energy savings potentials under the BAU identified in this study are lower. There are two main reasons that can explain this difference: (a) in this analysis and under the BAU scenario, it was assumed that all new capacity installed in China and Russia adopts the energy efficient Bayer process

limiting therefore the future energy savings potential and (b) in this analysis, only the adoption of currently available measures was taken into consideration.

## Conclusion and recommendations

In this paper, we identified available measures to reduce the energy use and GHG emissions in the primary aluminium industry up to 2050 and constructed energy and GHG abatement curves to assess the technical and cost-effective energy and GHG savings potentials.

This study estimates that there is a technical potential to decrease the 2050 energy use in alumina refining by 31 % under the frozen efficiency scenario and by 12 % under the BAU scenario. The technical potential to decrease CO<sub>2</sub> emissions is identified at 33 % under the frozen efficiency scenario and 13 % under the BAU scenario.

The wide adoption of energy efficiency improvement measures in primary aluminium production (excluding alumina refining) has the technical potential to decrease the primary energy use by 9 % under the frozen efficiency scenario. In the BAU scenario, the technical potential (including only currently available technologies) is limited to 0.9 %.

Concluding, this study identified that under a frozen efficiency scenario, the 2050 primary energy use in the primary aluminium industry can be lowered by 1,636 PJ, equivalent to 13 % of the 2050 primary energy use, 740 PJ in alumina refining and 896 PJ in primary aluminium production (excl. alumina refining). Under a BAU scenario, the 2050 technical primary energy savings potential is 302 PJ equivalent to about 3 % of the 2050 primary energy use, 222 PJ in alumina refining and 81 PJ in primary aluminium production (excluding alumina refining).

In the frozen efficiency scenario, the countries with the highest primary energy savings potential are China (57 %), Russia (13 %), Australia (8 %) and India (8 %). For China and Russia, to achieve these high-energy savings potentials, better quality bauxite needs to be used. In a scenario in which China and Russia keep on processing local low-quality bauxite, the energy savings breakdown per country is different, China (46 %), Russia (14 %), Australia (11 %) and India (11 %). In the BAU scenario, the countries with the highest primary energy savings potential are China (71 %), Russia (11 %) and the USA (6 %).

The aim of this study was to identify the currently available energy efficiency measures that can play a significant role in mitigating GHG emissions in the primary aluminium industry and determine the cost of the investments required, assisting in this way policy makers to better understand the potentials for energy and GHG savings in this sector and construct effective and efficient industry specific policies. It was identified that the highest energy savings potentials in the primary aluminium industry from the widespread BPT adoption exists in the alumina refining industry. Concerning the smelting of aluminium, if no new technologies will become available in the coming years, there will only be a small potential for energy efficiency improvement and GHG emission reduction. To further reduce GHG emissions beyond energy efficiency, investments in RD&D in new technologies will need to be made, and the

decarbonization of the power sector will need to be promoted.

This analysis could be strengthened with the use of more country-specific data regarding energy consumption such as the energy use for alumina refining in Brazil and Russia and country-specific data regarding the energy use in less energy-intensive processes such as anode manufacture and ingot casting. More information regarding the energy efficiency improvement of the different energy saving measures and the change their implementation would have in the overall plant operation and maintenance costs. In addition, more information concerning the lifetime and retirement of equipment would allow to more explicitly model stock turnover. Furthermore, country-specific data on technology penetration levels would strengthen the implementation rates estimated for each measure. Areas in which further research could contribute into a better estimation of the future cost-efficient potentials are the development of future investment costs required for implementing the different technologies and the development of energy prices in each country. The inclusion of more measures such as efficient transformers in aluminium smelter facilities and cogeneration in alumina refineries and the inclusion of innovative measures that are likely to become commercially available in the future could increase the future energy and GHG savings potentials identified in this analysis.

## Appendix

**Table 14** Estimated shares of metallurgical alumina production and capacity utilization rates (based on regional data found in IAI 1013c)

Countries	2009 share of metallurgical alumina production on the total alumina production	2009 capacity utilization rates
China	96 %	87 %
Australia	98 %	100 %
Brazil	99 %	91 %
India	86 %	83 %
Russia	92 %	94 %
United States	83 %	61 %
<b>World</b>	<b>94 %</b>	<b>87 %</b>

**Table 15** Default CO<sub>2</sub> emission factors per fuel (IPCC, 2006a)

Fuel type	tonnes CO <sub>2</sub> /TJ
Residual fuel oil	77.4
Coal (anthracite)	98.3
Natural gas	56.1
Biofuels	0 <sup>1</sup>

<sup>1</sup>As biofuels are considered a renewable energy source we use a zero CO<sub>2</sub> emission factor

**Table 16** Fuel use breakdown in 2009 (based on IEA 2011a)

Countries	Coal	Oil	Natural gas	Biofuels and waste <sup>1</sup>	Heat	Other	Total
China	76 %	10 %	3 %	0 %	11 %	0 %	100 %
Russia <sup>2</sup>	14 %	16 %	30 %	0 %	40 %	0 %	100 %
Canada	0 %	1 %	99 %	0 %	0 %	0 %	100 %
United States	0 %	7 %	91 %	0 %	2 %	0 %	100 %
Australia	26 %	19 %	53 %	0 %	0 %	0 %	100 %
Brazil	7 %	68 %	25 %	0 %	0 %	0 %	100 %
Norway	0 %	47 %	53 %	0 %	1 %	0 %	100 %
India	71 %	29 %	0 %	0 %	0 %	0 %	100 %
United Arab Emirates <sup>2</sup>	0 %	4 %	96 %	0 %	0 %	0 %	100 %
Bahrain	0 %	0 %	100 %	0 %	0 %	0 %	100 %
South Africa <sup>2</sup>	89 %	11 %	0 %	0 %	0 %	0 %	100 %

<sup>1</sup> According to the IAI statistics (2013c), most of the fuel used in alumina refining is coal, gas and oil. Thus, for this analysis we set the share of biomass and waste on the overall fuel use to 0 %

<sup>2</sup> Due to non-reliable data concerning the fuel use in the non-ferrous metals industry in Russia, United Arab Emirates and South Africa, instead of the of the fuel mix breakdown in the non-ferrous metals industry, the fuel mix breakdown of the overall industrial sector is used

**Table 17** Fuel mix for the generation of electricity used in alumina refineries (based on IEA 2011a)

Countries	Coal	Oil	Natural gas	Nuclear	Hydro	Geothermal	Solar/wind/other	Biofuels and waste
Australia	78 %	1 %	14 %	0 %	5 %	0 %	2 %	1 %
United States	45 %	1 %	23 %	20 %	7 %	0 %	2 %	2 %
Canada	15 %	1 %	6 %	15 %	60 %	0 %	1 %	1 %
Norway	0 %	0 %	3 %	0 %	96 %	0 %	1 %	0 %
Bahrain	0 %	0 %	100 %	0 %	0 %	0 %	0 %	0 %
Brazil	2 %	3 %	3 %	3 %	84 %	0 %	0 %	5 %
China	79 %	0 %	2 %	2 %	16 %	0 %	1 %	0 %
India	69 %	3 %	12 %	2 %	12 %	0 %	2 %	0 %
Russia	17 %	2 %	47 %	17 %	18 %	0 %	0 %	0 %
South Africa	94 %	0 %	0 %	5 %	1 %	0 %	0 %	0 %
United Arab Emirates	0 %	2 %	98 %	0 %	0 %	0 %	0 %	0 %
<b>World</b>	<b>40 %</b>	<b>5 %</b>	<b>21 %</b>	<b>13 %</b>	<b>16 %</b>	<b>0 %</b>	<b>2 %</b>	<b>1 %</b>

**Table 18** Fuel mix for the generation of electricity used in aluminium smelters, anode production and ingot casting facilities

Countries	Coal	Oil	Natural gas	Nuclear	Hydro	Geothermal	Solar/wind/other	Biofuels and waste	Total
Australia	75 %	1 %	13 %	0 %	8 % <sup>1</sup>	0 %	2 %	1 %	100 %
United States <sup>2</sup>	58 %	0 %	1 %	1 %	39 %	0 %	0 %	0 %	100 %
Canada	0 %	0 %	0 %	0 %	100 % <sup>3</sup>	0 %	0 %	0 %	100 %
Norway	0 %	0 %	2 %	0 %	98 % <sup>4</sup>	0 %	0 %	0 %	100 %
Bahrain	0 %	0 %	100 % <sup>5</sup>	0 %	0 %	0 %	0 %	0 %	100 %
Brazil	1 %	2 %	2 %	2 %	90 % <sup>6</sup>	0 %	0 %	3 %	100 %
China <sup>7</sup>	85 %	0 %	2 %	2 %	10 %	0 %	1 %	0 %	100 %
India	39 %	2 %	7 %	1 %	50 % <sup>8</sup>	0 %	1 %	0 %	100 %
Russia	3 %	0 %	9 %	3 %	84 % <sup>9</sup>	0 %	0 %	0 %	100 %
South Africa <sup>10</sup>	94 %	0 %	0 %	5 %	1 %	0 %	0 %	0 %	100 %
United Arab Emirates	0 %	2 %	98 % <sup>11</sup>	0 %	0 %	0 %	0 %	0 %	100 %
<b>World<sup>12</sup></b>	<b>51 %</b>	<b>0 %</b>	<b>8 %</b>	<b>2 %</b>	<b>38 %</b>	<b>0 %</b>	<b>0 %</b>	<b>0 %</b>	<b>100 %</b>

<sup>1</sup> USGS 1998; Turton 2002

<sup>2</sup> Green 2007

<sup>3</sup> USGS 1998; also according to own estimations based on CIEEDAC (2012) hydropower for aluminium smelting in Canada accounts for more than 97 % of the electricity used

<sup>4</sup> NVE 2009

<sup>5</sup> USGS 1998

<sup>6</sup> EPE 2013

<sup>7</sup> IAI 2013c

<sup>8</sup> Bhushan 2010

<sup>9</sup> USGS 1998; Gurov 2003

<sup>10</sup> Due to the lack of data for South Africa, the same fuel mix as in Table 17 is used

<sup>11</sup> USGS 1998; DUBAL 2010

<sup>12</sup> IAI 2013c

**Table 19** Electricity conversion efficiency<sup>1</sup> (based on IEA 2011a)

Countries	Coal	Oil	Natural gas	Nuclear	Hydro	Geothermal	Solar/wind/other	Biofuels and waste
Australia	35 %	36 %	39 %	–	100 %	–	100 %	15 %
United States	37 %	40 %	48 %	33 %	100 %	18 %	99 %	33 %
Canada	42 %	29 %	40 %	33 %	100 %	–	100 %	38 %
Norway	38 %	N/A	56 %	–	100 %	–	101 %	34 %
Bahrain	–	–	30 %	–	–	–	–	–
Brazil	32 %	39 %	46 %	33 %	100 %	–	100 %	47 %
China	34 %	35 %	40 %	33 %	100 %	10 %	100 %	25 %
India	27 %	21 %	41 %	33 %	100 %	–	100 %	15 %
Russia	32 %	30 %	33 %	33 %	100 %	10 %	–	25 %
South Africa	34 %	35 %	–	33 %	100 %	–	91 %	25 %
United Arab Emirates	–	25 %	32 %	–	–	–	–	–
<b>World</b>	<b>35 %</b>	<b>40 %</b>	<b>42 %</b>	<b>33 %</b>	<b>100 %</b>	<b>10 %</b>	<b>102 %</b>	<b>31 %</b>

<sup>1</sup> The method used to determine the conversion efficiencies per fuel type in each country was the “power loss factor” method (see Graus and Worrell 2011). A correction factor of 0.18 and 0.22 was used for public heat and auto-producers, respectively, to account for the electricity that would have been generated in case no heat was produced (Graus and Worrell 2011)

**Table 20** GDP growth rates (2009–2035 based on regional growth rates reported in IEA (2011c) and 2035–2050: Graus and Kermeli (2012))

Countries	2009–2020	2020–2035	2035–2050	2009–2050
China	8.17 %	4.24 %	2.70 %	4.69 %
Russia	4.19 %	3.34 %	1.80 %	3.00 %
Canada	3.33 %	2.47 %	1.20 %	2.23 %
Australia	3.22 %	2.00 %	0.70 %	1.85 %
USA	2.57 %	2.20 %	1.10 %	1.89 %
India	7.62 %	5.82 %	3.10 %	5.30 %
Brazil	4.37 %	3.16 %	2.60 %	3.27 %
Norway	2.13 %	1.84 %	1.00 %	1.61 %
United Arab Emirates	4.27 %	3.75 %	2.80 %	3.54 %
Bahrain	4.27 %	3.75 %	2.80 %	3.54 %
South Africa	4.49 %	4.40 %	4.20 %	4.36 %
<b>World</b>	<b>4.20 %</b>	<b>3.18 %</b>	<b>2.20 %</b>	<b>3.08 %</b>

**Table 22** Shares of high temperature and low temperature digestion

Countries	High-temperature digestion	Low-temperature digestion
China	60 %	40 %
Australia	24 %	76 %
Brazil	0 %	100 %
India	15 %	85 %
United States	85 %	15 %
Russia	60 %	40 %

**Table 21** Estimated current energy savings potentials in alumina refining per country

Countries	Current (GJ/tonne)	BPT (Low-T) (GJ/tonne)	BPT (High-T) <sup>1</sup> (GJ/tonne)	BPT (average) <sup>2</sup> (GJ/tonne)	Energy savings potential
China <sup>3</sup>	19.4	9.0	10.0	9.1	−53 %
Australia	10.5	9.0	10.0	9.2	−12 %
Brazil	9.6	9.0	10.0	9.0	−6 %
India	14.4	9.0	10.0	9.2	−36 %
Russia <sup>3</sup>	27.9	9.0	10.0	9.0	−67 %
United States	14.4	9.0	10.0	9.9	−32 %

<sup>1</sup> The HT BPT is based on the energy use at the Yarwun (formerly Comalco) alumina refinery in Australia. The Yarwun refinery processes boehmitic bauxite at high temperature with tube digestion and has an energy use of less than 10 GJ/t alumina (Rio Tinto Alcan 2010)

<sup>2</sup> Based on the shares of high and low temperature digestion in each country (see Table 22)

<sup>3</sup> In the case of China and Russia the energy savings potentials are based on the assumption that China and Russia have access to better quality bauxite and all alumina refineries use the Bayer process

**Table 23** Estimated implementation rates<sup>1</sup>- alumina refining - frozen efficiency scenario

No.	Measures	China	Australia	Brazil	India	Russia	United States
	Digestion						
1	Sweetening – HT Plants <sup>2</sup>	7 %	0 %	0 %	5 %	0 %	0 %
2	Tube digestion+Indirect heating – HT Plants <sup>3</sup>	13 %	20 %	0 %	15 %	0 %	85 %
	Clarification						
3	Install high rate thickeners - High Temp Plants	9 %	2 %	0 %	15 %	0 %	26 %
	Install high rate thickeners - Low Temp Plants	61 %	8 %	10 %	85 %	20 %	5 %
	Precipitation						
4	Implement seed filtration - HT Plants	9 %	2 %	0 %	15 %	0 %	26 %
	Implement seed filtration - LT Plants	61 %	8 %	10 %	85 %	20 %	5 %
5	Implement inter-stage cooling - HT Plants	9 %	2 %	0 %	15 %	0 %	26 %
	Implement inter-stage cooling - LT Plants	61 %	8 %	10 %	85 %	20 %	5 %
	Heat Interchange						
6	Direct cooling - HT Plants	9 %	2 %	0 %	15 %	0 %	26 %
	Direct cooling - LT Plants	61 %	8 %	10 %	85 %	20 %	5 %
	Calcination						
7	Kiln retrofit	66 % <sup>4</sup>	12 % <sup>5</sup>	20 % <sup>6</sup>	17 % <sup>7</sup>	89 % <sup>8</sup>	20 % <sup>6</sup>
8	Optimize cyclone operation	70 %	10 %	10 %	100 %	20 %	30 %
9	Install a “hydrate-by-pass” system <sup>9</sup>	70 %	10 %	10 %	100 %	20 %	30 %
10	Improve waste heat recovery	70 %	10 %	10 %	100 %	20 %	30 %
	Overall Process						
11	Advanced control	70 %	10 %	15 %	100 %	20 %	30 %
12	Combined Bayer-Sinter→Bayer-Flotation, Lime-Bayer	11 %	0 %	0 %	0 %	92 %	0 %
	Sinter→Bayer-Flotation, Lime-Bayer	3 %	0 %	0 %	0 %	8 %	0 %
13	Combined Bayer-Sinter→Bayer-LT	11 %	0 %	0 %	0 %	92 %	0 %
	Sinter→Bayer-LT	3 %	0 %	0 %	0 %	8 %	0 %
	Bayer-Flotation, Lime-Bayer Process→Bayer-LT	73 %	0 %	0 %	0 %	0 %	0 %

<sup>1</sup> Author own estimations. When no information is available the implementation rates are based on the energy savings potentials from wide BPT adoption (see Table 21)

<sup>2</sup> Sweetening can only be implemented on high temperature digestion (see Table 22). As this measure has already been implemented in many countries (IAI, 2013a), the implementation rate is significantly lower than the share of high temperature digestion

<sup>3</sup> Tube digestion has only been adopted in two alumina refineries (IPTS/EC, 2013); the Rio Tinto Alcan Yarwun (formerly known as Comalco) alumina refinery (1.4 mtpa) in Australia (responsible for about 7 % of Australian alumina production in 2009) (Rio Tinto Alcan, 2010), and one refinery in Germany (IPTS/EC, 2013; Hudson et al., 2005). Thus, the implementation rate for this technology for every country in this study is equal to the share of high temperature digestion (see Table 22). Exceptions are i) Australia for which the implementation rate is lowered by 7 %, ii) China where due to the inclusion of measures “Combined Bayer-Sinter→Bayer”, “Sinter→Bayer” and “Bayer-Flotation, Lime-Bayer→Bayer” the majority of alumina is produced with the low temperature Bayer process and iii) Russia where again due to the inclusion of the process switch measures no alumina will be produced with the high temperature Bayer process

<sup>4</sup> According to Wind and Raahauge (2013), most plants built in China after 2005 employ gas suspension calciners. Chinese alumina capacity increased from 18.5 Mtonnes in 2005 to 28 Mt in 2009 (USGS, 2007a, 2007b, 2010a, 2010b, 2011). Thus, in 2009, at least 34 % of alumina capacity uses stationary calciners

<sup>5</sup> Author own estimations based on available capacity and technology information (AAC, 2013; NTEPA, 2004; Williams and Schmidt, 2012; Alcoa, 2007; Wind and Raahauge, 2013; Alcoa, 2005; Outotec, 2011)

<sup>6</sup> Due to the lack of information assumed equal to the world average (20 %) (Williams and Schmidt, 2012)

<sup>7</sup> Author own estimations based on available capacity and technology information (EMT-India, 2004; PIB, 2003; Ministry of environment and forests & Ministry of defense 2008; Hindalco, 2004; Hindalco, 2013)

<sup>8</sup> Author own estimation based on capacity and technology information found in UC RUSAL (2010)

<sup>9</sup> Hydrate by-pass was developed in the 1990s and is installed in 6 plants worldwide (Klett et al., 2011). Thus, for this study we assume a high implementation rate



**Table 24** Estimated implementation rates - aluminium smelting - frozen efficiency scenario

Measures	China <sup>1</sup>	Russia <sup>2</sup>	Canada <sup>3</sup>	Australia <sup>4</sup>	United States <sup>5</sup>	India <sup>6</sup>	Brazil <sup>7</sup>	Norway <sup>3</sup>	United Arab Emirates <sup>3</sup>	Bahrain <sup>3</sup>	South Africa <sup>3</sup>
VSS→PFPB <sup>8</sup>	0 %	52 %	22 %	0 %	17 %	19 %	39 %	0 %	0 %	0 %	12 %
HSS→PFPB <sup>8</sup>	0 %	13 %	2 %	0 %	1 %	1 %	3 %	0 %	0 %	0 %	1 %
SWPB→PFPB <sup>8</sup>	2 %	1 %	1 %	0 %	1 %	1 %	1 %	2 %	2 %	2 %	2 %
CWPB→PFPB <sup>8</sup>	0 %	1 %	0 %	100 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
Optimized cell operation <sup>9</sup>	40 %	10 %	30 %	25 %	60 %	40 %	40 %	0 %	40 %	40 %	40 %

<sup>1</sup> According to Gao et al. (2009), all Chinese smelters use the prebake technology

<sup>2</sup> UC Rusal, 2010

<sup>3</sup> Since no more recent data could be retrieved, the USGS (1998) data for 2003 are used

<sup>4</sup> According to the Commonwealth Government Initiative (2000) all primary aluminium production in the late 90s in Australia took place in CWPB cells

<sup>5</sup> According to Green (2007) in 2005, 82 % of U.S. primary aluminium was produced in prebake cells

<sup>6</sup> According to Bhushan (2010) in 2003, 80 % of primary aluminium capacity used the prebake technology

<sup>7</sup> According to CNI (2012) in 2010, 58 % of primary aluminium capacity used the prebake technology

<sup>8</sup> Specific information on the type of Söderberg and prebake technologies used could only be retrieved for Australia and Russia. For the remaining countries, the implementation rates are estimated based on world ratios. For prebake technology (non-Australia) that is 98 % PFPB, 0 % CWPB and 2 % SWPB. For Söderberg technology (non-Russia) that is 93 % VSS and 7 % HSS

<sup>9</sup> Due to the lack of information the implementation rates for this measure were estimated based on the energy savings potential from BPT adoption

**Table 25** Energy efficiency measures for the alumina refining industry ranked based on their  $CCE_{final}$  (discount rate=30 %)-(switch alternative processes used in China and Russia to the Bayer-flotation instead of the Bayer)

Efficiency measures	"Frozen-efficiency"				"Business-as-usual"				Associated costs		
	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO <sub>2</sub> )	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO <sub>2</sub> )	final energy savings (PJ)	primary energy savings (PJ)	GHG emissions savings (MtCO <sub>2</sub> )	Cost of conserving energy (\$/GJ)	Cost of mitigating GHGs (\$/ktCO <sub>2</sub> )
Advanced control	35	39	3.4	0	0	0.0	-10.6				-107
Optimized cyclone operation	12	13	1.1	0	0	0.0	-8.6				-91
Sinter → Bayer-flotation	45	45	3.9	0	0	0.0	-5.6				-65
Sweetening	7	7	0.6	0	0	0.0	-2.0				-22
Tube digestion + indirect heating	93	93	7.1	8	9	0.6	-1.1				-14
Inter-stage cooling - HT Plants	3	3	0.3	0	0	0.0	-1.1				-13
Direct cooling - HT Plants	3	3	0.2	0	0	0.0	-0.6				-7
Inter-stage cooling - LT Plants	17	17	1.5	0	0	0.0	-0.4				-4
Seed filtration - HT Plants	8	8	0.6	1	1	0.1	-0.2				-2
<b>Total "cost-effective"</b>	<b>221</b>	<b>227</b>	<b>18.8</b>	<b>9</b>	<b>10</b>	<b>0.7</b>					
Direct cooling - HT Plants	10	10	0.8	1	1	0.1	1.7				19
Seed filtration - LT Plants	31	31	2.8	2	5	0.2	1.8				20
High rate thickeners - HT Plants	2	2	0.1	1	1	0.0	4.0				47
Kiln retrofit	76	76	6.5	27	27	1.9	4.4				52
"Hydrate-by-pass" system	5	5	0.4	2	2	0.2	6.2				71
High rate thickeners - LT Plants	7	7	0.6	3	3	0.3	7.1				81
Combined Bayer-Sinter → Bayer-flotation	106	106	8.6	45	45	3.7	8.1				100
Improved waste heat recovery	5	5	0.4	3	3	0.2	17.1				195
<b>Total "technical"</b>	<b>463</b>	<b>468</b>	<b>39.2</b>	<b>94</b>	<b>96</b>	<b>7.2</b>					

**Table 26** Energy and GHG savings potentials for primary aluminium production (excl. alumina refining) per country

Countries	2050 primary aluminium production (Mtonnes)	Final energy savings (PJ)				Primary energy savings (PJ) <sup>1</sup>				GHG savings (MCO <sub>2</sub> -eq.) <sup>1</sup>			
		frozen efficiency		BAU		frozen efficiency		BAU		frozen efficiency		BAU	
		technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective	technical	cost-effective
China	34	134	139	7	9	317	325	17	18	28.1	31.3	1.5	1.6
Russia	10	3	69	0	5	3	195	0	18	0.2	15.6	0.0	0.9
Australia	3	2	31	0	5	2	81	0	12	0.2	8.4	0.0	1.0
United States	3	3	22	0	7	4	54	0	19	0.2	3.8	0.0	1.2
India	13	11	77	0	4	19	238	0	12	1.7	23.6	0.0	1.0
Brazil	4	2	32	0	1	2	39	0	2	0.2	2.1	0.0	0.0
Canada	6	3	32	0	11	3	52	0	19	0.2	3.0	0.0	0.5
Norway	2	1	2	0	1	1	2	0	1	0.1	0.2	0.0	0.0
United Arab Emirates	3	0	12	0	1	0	34	0	1	0.0	2.1	0.0	0.1
Bahrain	2	0	10	0	0	0	30	0	1	0.0	1.9	0.0	0.1
South Africa	3	1	16	0	1	1	44	0	4	0.1	4.6	0.0	0.4
<b>Total</b>	<b>83</b>	<b>162</b>	<b>442</b>	<b>8</b>	<b>44</b>	<b>353</b>	<b>1093</b>	<b>18</b>	<b>106</b>	<b>30.9</b>	<b>96.7</b>	<b>1.6</b>	<b>6.8</b>

<sup>1</sup> The fuel mix for electricity generation is the country average based on IEA (2011a) (see Table 17)

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