3rd International Conference on Energy, Environment and Economics, ICEEE2018, 14-16 August 2018, Edinburgh Conference Centre, Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom

Impact analysis of energy efficiency measures in the electrolysis process in primary aluminium production

Joakim Haraldsson*, Maria Therese Johansson

Division of Energy Systems, Department of Management and Engineering, Linköping University, SE-58183, Sweden

Corresponding author's mail: joakim.haraldsson@liu.se

Abstract

The Paris Agreement includes the goals of 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels' and 'making finance flows consistent with a pathway towards low greenhouse gas emissions'. Industrial energy efficiency will play an important role in meeting those goals as well as becoming a competitive advantage due to reduced costs for companies. The aluminium industry is energy intensive and uses fossil fuels both for energy purposes and as reaction material. Additionally, the aluminium industry uses significant amounts of electricity. The electrolysis process in the primary production of aluminium is the most energy- and carbon-intensive process within the aluminium industry. The aim of this paper is to study the effects on primary energy use, greenhouse gas emissions and costs when three energy efficiency measures are implemented in the electrolysis process. The effects on the primary energy use, greenhouse gas emissions and costs are calculated by multiplying the savings in final energy use by a primary energy factor, emissions factor and price of electricity, respectively. The results showed significant savings in primary energy demand, greenhouse gas emissions and cost from the implementation of the three measures. These results only indicate the size of the potential savings and a site-specific investigation needs to be conducted for each plant. This paper is a part of a research project conducted in close cooperation with the Swedish aluminium industry.

Keywords: Energy efficiency; Aluminium industry; Primary aluminium production; Electrolysis; Primary energy use; Greenhouse gas emissions; Cost saving

Abbreviations

EmF	Emission factor
GHG	Greenhouse gas
PEF	Primary energy factor
PFC	Perfluorocarbons

1. Introduction

The Paris Agreement includes goals on 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels' and 'making finance flows consistent with a pathway towards low greenhouse gas emissions' [1]. In 2010, 21% of the total global greenhouse gas (GHG) emissions were direct emissions from the industrial sector [2]. An additional 11% of the total global GHG emissions were indirect emissions resulting from the industrial sector's use of electricity and heat [2]. Industrial energy efficiency will play an important role in meeting the goals of the Paris Agreement as well as becoming a competitive advantage due to lowered operating costs. The production of aluminium, especially primary (virgin) aluminium, is both energy- and GHG-intensive [3]. The electrolysis process within the primary aluminium production is by far the most energy- and GHG-intensive process in the aluminium industry [3].

The electrolysis process, also called the Hall-Héroult process, is based on the electrical reduction of aluminium oxide to pure aluminium and uses electricity as the main energy carrier [4]. Fossil coal in the form of carbon anodes is used to facilitate the electrical reduction, resulting in CO_2 and CO emissions [4]. In addition, there are disturbances in the process, so-called 'anode effects', where an insufficient amount of aluminium oxide is dissolved in the electrolyte bath, resulting in the emission of perfluorocarbons(PFCs)[5]. Therefore, the climate impact from electrolysis maybe divided into three parts: (1) GHG emissions due to the use of electricity; (2) the emission of CO_2 and CO due to the consumption of anodes; and (3) the emission of PFCs during anode effects.

The primary energy factor (PEF) is generally calculated as the amount of primary energy divided by the delivered energy [6]. The primary energy is the energy needed to deliver one unit of final energy, which should include the energy needed for activities including, for example, the following: extraction, processing, storage, generation, transformation and distribution [6]. However, the PEF can be calculated in different ways [7]. For electricity, the simplest method of calculation is to divide the fuel demand of the electricity production unit by the amount of electricity generated [7]. However, this may provide misleading values for the PEF, since factors such as transmission losses and energy used for extracting, cleaning and transporting the fuel are not considered [7].

The aim of this paper is to study the effects on primary energy use, GHG emissions and costs when three energy efficiency measures are implemented in the electrolysis process during primary aluminium production.

2. Methodology

Our calculations are based on a hypothetical electrolysis plant located in Sweden with the characteristics shown in Table 1. The electrolysis plant is assumed to use prebaked anode technology, since about 95% of primary aluminium production worldwide uses this technology [8]. The values for the energy intensity, GHG emissions

from anode consumption and PFC emissions are based on data and statistics from the International Aluminium Institute, and world averages were chosen. The value for annual production was chosen based on common industry values.

Table 1Characteristics of the hypothetical electrolysis plant

	Used value	Reference
Energy intensity	14.318 kWh/kg Al	[9]
GHG emissions due to anode consumption	1.503 kg CO_2eq/kg Al	[8]
PFC emissions due to anode effect	0.63 kg CO_2eq/kg Al	[5]
Production	200 000 tonne Al/year	

The three energy efficiency measures chosen for the investigation include the following: (1) Slotted or perforated anodes ;(2) A distributed pot suction system; and (3) Use of a fuzzy controller combined with mathematical models to predict the process temperature. A description of the measures is given in [4]. The potential energy savings for the measures are shown in Table 2.

Table 2 Potential energy savings for the studied energy efficiency measures [4]

Energy efficiency measure	Energy saving
Slotted or perforated anodes	0.781 kWh/kg Al
Distributed pot suction system	0.4 kWh/kg Al
Fuzzy controller combined with mathematical models to predict the process temperature	0.6 kWh/kg Al

The amount of primary energy, GHG emissions and cost saved per kilogram of aluminium for the three measures were calculated by multiplying the energy-saving potentials in Table 2by the PEF, emissions factor (EmF) and price for electricity, respectively. The PEF, EmF and prices used are shown in Table 3, which lists values for both Swedish and European electricity mixes. Values for a Swedish electricity mix were used because the electrolysis plant was assumed to be located in Sweden. European values were also used, since the Swedish electricity market is connected to the European electricity market, and trading of electricity occurs between Sweden and the rest of Europe.

Table 3PEF, EmF and prices for Swedish and European electricity

	Swedish electricity	European electricity	Unit	Reference
PEF	1.7	2.5	–	[10]
EmF	0.046	0.432	kg CO_2eq/kWh	[11]
Price	0.065	0.114	EUR/kWh	[12]

After calculating the savings per kilogram of aluminium, the total savings for the entire plant were calculated by multiplying by the annual production, listed in Table 1.

3.   Results and analysis

The potential savings in primary energy demand are shown in Fig.1. The savings percentage for each measure is the same using either Swedish or European electricity, and correspond to the percentage of savings in the final energy use. The savings percentage is calculated by dividing the energy savings by the energy demand before the measure is implemented. When calculating the savings percentage in primary energy demand, both the energy savings in Table 2 and the energy intensity in Table 1 are multiplied by the PEF. The PEF is then cancelled out when dividing the values by each other, which explains why the savings percentages are the same when using either Swedish or European electricity, but also why the savings values correspond to the savings percentages in final energy demand.
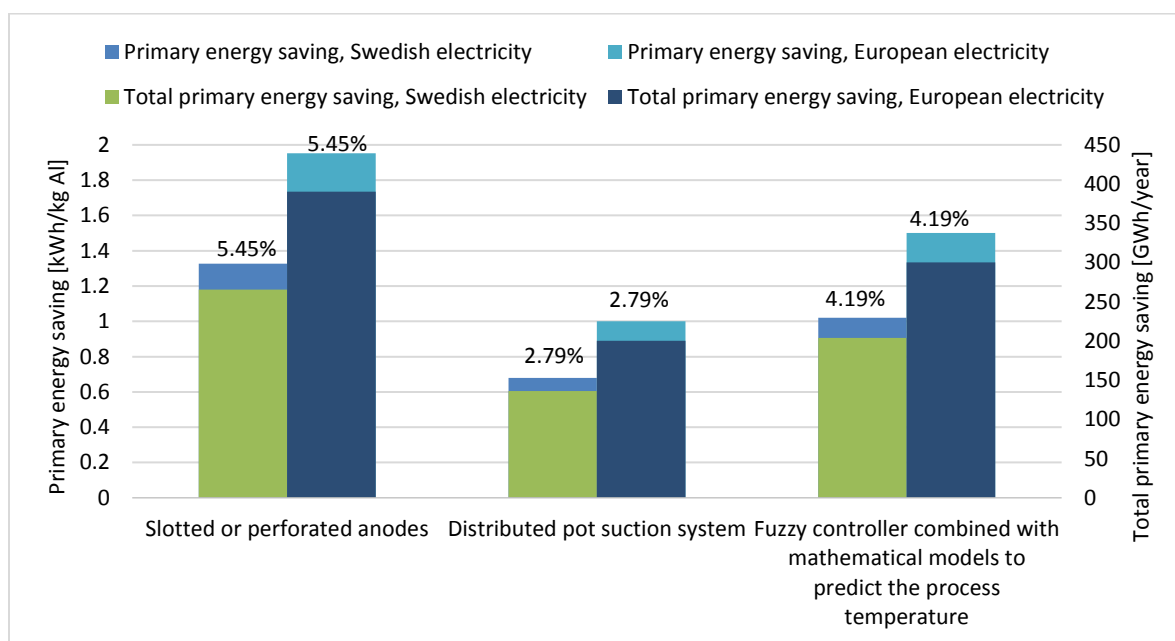

Fig.1 Potential savings in primary energy demand

Fig.2 shows the potential savings in GHG emissions. The savings percentages for the GHG emissions are lower than the savings percentages in primary energy demand because electricity use is only one part of the total GHG emissions associated with electrolysis, as outlined in the introduction. The savings percentage when using the European electricity mix is higher than that when using the Swedish electricity mix, as the electricity use constitutes a larger share of the total GHG emissions from the electrolysis due to the higher emission factor for European electricity.
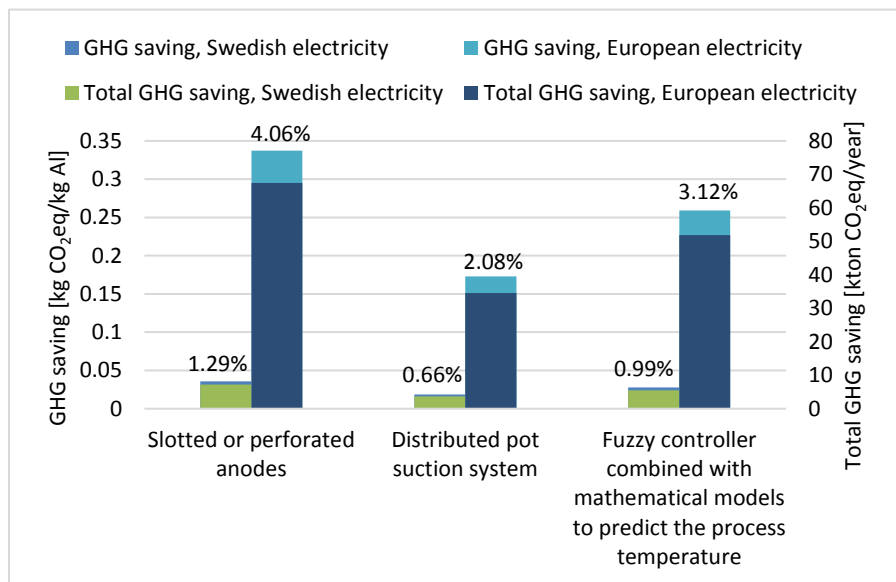
Fig.2 Potential savings in GHG emissions

Fig.3 shows the potential cost savings, although no values for the production costs of primary aluminium through electrolysis are available. As a result, the savings percentage could not be calculated with regards to the total production costs. However, the savings percentage when considering only the electricity costs for electrolysis will be the same as the percentage savings presented in Fig. 1, because a certain savings percentage in energy demand will provide an equally large savings percentage in electricity cost.
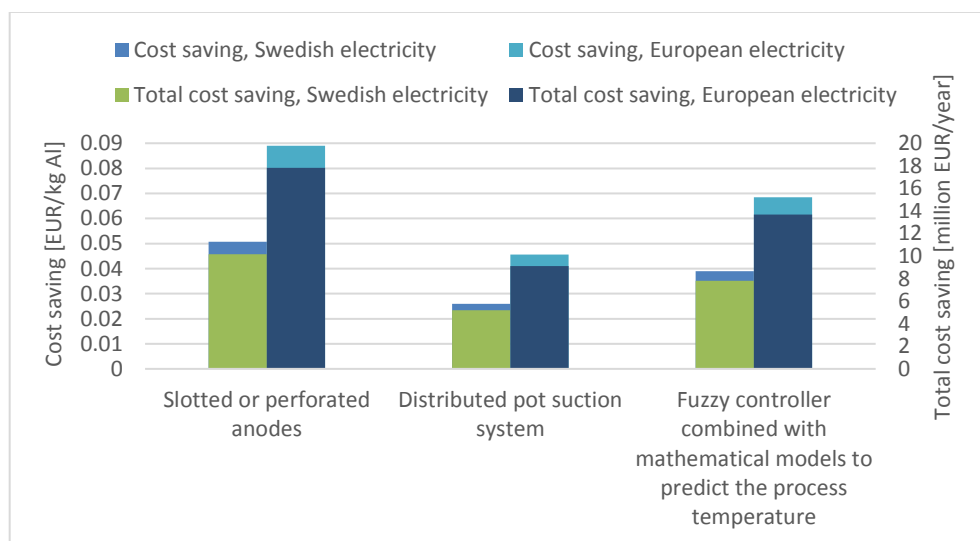

Fig.3 Potential savings in electricity cost

4. Discussion

Significant savings in primary energy demand, GHG emissions and cost arise from the implementation of the three measures, as shown in Fig. 1, Fig. 2 and Fig. 3. The largest savings arise from implementing the slotted or perforated anodes, although each measure maybe implemented without impeding the implementation of the other measures[4], implying that the largest total savings would arise from implementing all three measures together. However, the total savings from the joint implementation of the three measures would probably be lower than the sum of the individual savings [4].

The results show that the savings potential for primary energy, GHG emissions and cost vary depending on the electricity mix used. The savings potentials when using the European electricity mix is higher than that achieved when using the Swedish electricity mix because the PEF, emission factor and price are higher for European electricity than for Swedish electricity. It is obvious that the type of electricity used and how it is generated has significant effects on the primary energy demand, GHG emissions and cost of the electricity use, and thus on the potential savings from energy efficiency. It is worth remembering that the electrolysis plant used in this paper is hypothetical. The characteristics of the plant, listed in Table 1, and the energy savings potentials, listed in Table 2, may, of course, vary from plant to plant. The type of electricity used at an electrolysis plant depends on the plant's contract with its electricity supplier. About 30% of the electricity used for electrolysis worldwide is generated from company-owned electricity production units [13].Therefore, the electricity used at an electrolysis plant may not be the same as the average electricity mix for the country or region where the plant is located. The primary energy factor, emission factor and price of the electricity vary from plant to plant. While the results of this paper may indicate the sizes of potential savings, the values and results presented cannot be assumed to be valid for all electrolysis plants in the world. Instead, a site-specific investigation is required for each case.

As stated in the introduction, there are different ways to calculate the PEF based on the numerous factors affecting the amount of primary energy needed to supply one unit of electricity [7]. The applied criteria, for example, precision in reflecting reality, simplicity and transparency, affect how a PEF is calculated and used [7]. The PEF value of 2.5 for the European electricity used in these calculations was collected from a document published by the Swedish Energy Agency [10] which corresponds with the value given in Annex IV of Directive 2012/27/EU, and is calculated on an average, European-wide conversion efficiency of 40%, excluding grid losses [7]. The PEF for Swedish electricity is calculated in a similar way [10]. Although this approach has been criticised for being overly simplified [7], which may affect the reliability of the results regarding primary energy savings, the results may still indicate the sizes of the potential savings.

5. Conclusions

Significant savings in primary energy demand, GHG emissions and cost arise from the implementation of the three measures described in this paper. The largest savings would arise from the joint implementation of all three measures. The savings would vary from plant to plant, depending on the type of electricity used and how it is generated, implying that a site-specific investigation needs to be conducted for each case. The results of this paper cannot be generalised to all electrolysis plants in the world but, may indicate the size of the potential savings.

ORCID Ids of Authors

Joakim Haraldsson: http://orcid.org/0000-0002-6790-3867
Maria Therese Johansson: https://orcid.org/0000-0003-0360-6019

References

[1] United Nations (2015) Paris Agreement. Available from: http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf [Accessed 23 March 2018].

[2] IPCC (2014) Climate Change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK & New York, NY, USA.

[3] Milford, R.L., Allwood, J.M., Cullen, J.M. (2011) Assessing the potential of yield improvements, through process scrap reduction, for energy and CO_2 abatement in the steel and aluminium sectors. Resources, Conservation and Recycling. 55(12), 1185-1195.

[4] Haraldsson, J., Johansson, M.T. (2018) Review of measures for improved energy efficiency in production-related processes in the aluminium industry: From electrolysis to recycling. Renewable and Sustainable Energy Reviews. 93, 525-548.

[5] The International Aluminium Institute (2017) Perfluorocarbon (PFC) emissions. Available from: http://www.world-aluminium.org/statistics/perfluorocarbon-pfc-emissions/ [Accessed 25 May 2018].

[6] Latõšov, E., Volkova, A., Siirde, A., Kurnitski, J., Thalfeldt, M. (2017) Primary energy factor for district heating networks in European Union member states. Energy Procedia. 116, 69-77.

[7] Esser, A., Sensfuss, F. (2016) Evaluation of primary energy factor calculation options for electricity. Fraunhofer-Institute für System- und Innovationsforschung (ISI). Available from: https://ec.europa.eu/energy/sites/ener/files/documents/final_report_pef_eed.pdf[Accessed 25 May 2018].

[8] The International Aluminium Institute (2017) 2015 Life cycle inventory data and environmental metrics. Available from: http://www.world-aluminium.org/publications/[Accessed 25 May 2018].

[9] The International Aluminium Institute (2017) Primary aluminium smelting energy intensity. Available from: http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/ [Accessed 25 May 2018].

[10] Brandsma, E.,Persson, T. (2015) Energimyndighetens syn på viktnings- och primärenergifaktorer [The Swedish Energy Agency's view on weighting and primary energy factors]. Swedish Energy Agency.

Available from: https://www.energimyndigheten.se/globalassets/om-oss/stallningstaganden/energimyndighetens-syn-pa-viktningsfaktorer.pdf [Accessed 16 April 2018].

[11] Moro, A., Lonza, L. (2017) Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles. Transportation Research Part D: Transport and Environment, In Press.

[12] Eurostat (2018) Electricity price statistics. Available from: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics [Accessed 16 April 2018].

[13] The International Aluminium Institute (n.d.) Energy & Water. Available from: http://primary.world-aluminium.org/aluminium-facts/energy-water/ [Accessed 1 June 2018].